U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-255 260

AIRFLOW STUDY RELATED TO EPA FIELD MONITORING PROGRAM

DENVER METROPOLITAN AREA. NOVEMBER, 1973

L[redacted] W. CROW

PREPARED FOR

NATIONAL ENVIRONMENTAL RESEARCH CENTER

1 FEBRUARY 1974

21 0075

PB 255 260

AIRFLOW STUDY RELATED TO EPA FIELD MONITORING PROGRAM DENVER METROPOLITAN AREA NOVEMBER, 1973

Prepared for

CHEMISTRY AND PHYSICS LABORATORY

ENVIRONMENTAL PROTECTION AGENCY

EPA Region VIII LIBRARY
Denver, Colorado

By

LOREN W. CROW
Certified Consulting Meteorologist

February 1, 1974

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

LWC # 128

BIBLIOGRAPHIC DATA SHEET	1. Report No. LWC-128	2.	3. Recipient's Accession No. PB-255 260
4. Title and Subtitle Airflow Study Related to EPA Field Monitoring Program, Denver Metropolitan Area. November, 1973.			5. Report Date 1 Feb 74 6.
7. Author(s) Loren W. Crow			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Loren W. Crow Denver, Colorado			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address National Environmental Research Center Research Triangle Park, N. C. Chemistry and Physics Lab.			13. Type of Report & Period Covered 14.

15. Supplementary Notes
Prepared in cooperation with National Environmental Research Center, Research Triangle Park, N. C. Chemistry and Physics Lab.

16. Abstracts
This report covers a summary of airflow patterns related to several air pollution episodes during November, 1973. The author assisted in selecting appropriate days for concentrated collection of air samples throughout the Denver metropolitan area. It was also his responsibility to coordinate the collection of pilot balloon (pibal) data at three locations on sampling days and to collect a photographic record from advantageous points.

This airflow study adds to the body of data which has previously been collected during special study periods in the Denver metropolitan area.

17. Key Words and Document Analysis. 17a. Descriptors
*Atmospheric motion,
*Air pollution,
Transport properties,
Combustion products,
Plumes,
Exhaust emissions,
Airports,
Graphic methods,
Photographs,
Monitoring,
Concentration(composition),
Maps,
Wind velocity,
Meteorological balloons,
Colorado.

17b. Identifiers/Open-Ended Terms
*Denver(Colorado).

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
National Technical Information Service Springfield, Virginia 22161	UNCLASSIFIED	69p
	20. Security Class (This Page) UNCLASSIFIED	22. Price 4.50/2.25

FORM NTIS-35 (REV. 10-73) ENDORSED BY ANSI AND UNESCO. THIS FORM MAY BE REPRODUCED USCOMM-DC 8265-P74

TABLE OF CONTENTS

	Page No.
Summary	i.
Introduction	1
Data Sources and Their Location	2
Importance of Air Stability	7
Detailed Pollution Episode Periods	18
Episode Days November 6-7	19
Episode Days November 9-10	28
Episode Day November 14	35
Episode Days November 16-17	40
Episode Days November 20-21	47
Episode Day November 24	54
Episode Days November 29-30	59
Acknowledgements	64

Figures follow after page when first mentioned in text.

COLOR ILLUSTRATIONS REPRODUCED IN BLACK AND WHITE

SUMMARY

1. During pollution episode days in Denver, Colorado, it is typical that airflow nearly reverses from downslope to upslope during late forenoon hours. A return to drainage flow takes place gradually in the early evening hours. These multiple changes in general airflow eliminate any possible use of a Steady State Flow concept for dense pollution days. for 24 hrs, etc

2. Depth of the visible polluted layer is directly related to surface heating during daylight hours. The top of the polluted layer matches the upper end of a dry adiabatic lapse rate line as it progresses upward along the morning temperature inversion profile with warmer surface temperatures.

3. During early afternoon hours there is frequently a detectable air motion carrying polluted air from over Denver toward the west and/or southwest. This air moving toward the mountains replaces air which has already been vertically mixed upward along the relatively warmer mountain slopes. The inversion is broken first over the higher terrain where less solar heating is required to eliminate the more shallow early morning temperature inversions.

4. There is good evidence that during forenoon hours "Heat Island" effects are often observed to produce an elevated plume moving beyond the downtown area toward the north-northeast. This "Heat Island Plume" continues until surface heating eliminates the coldest layer near the ground.

5. There is some evidence that a "chimney effect" is produced near the north end of the "Heat Island" in the hours from 0600 through 1000. This "chimney effect" can help draw air from north to south near the surface in the lower part of the valley a few miles north-northeast of the downtown area.

INTRODUCTION

This report covers a summary of airflow patterns related to several air pollution episodes during November, 1973. The sponsoring agency was the Atmospheric Aerosol Research Section, Chemistry and Physics Laboratory, Environmental Protection Agency, National Environmental Research Center - Research Triangle Park, North Carolina. The author assisted in selecting appropriate days for concentrated collection of air samples throughout the Denver metropolitan area. It was also his responsibility to coordinate the collection of pilot balloon (pibal) data at three locations on sampling days and to collect a photographic record from advantageous points.

This airflow study adds to the body of data which has previously been collected during special study periods in the Denver metropolitan area. Summary reports of those studies are included in:

Riehl, H., & L. W. Crow, 1962, "A Study of Denver Air Pollution", Atmospheric Science Technical Report No. 33, Colorado State Univ.

Crow, L.W., 1964, "Airflow Related to Air Pollution at Colorado Springs, Denver, Durango, Grand Junction, and Pueblo", for State Department of Public Health, State of Colorado, LWC #44. (Not published.)

Reiter, E.R., N. Djordjevic, W. Ehrman, G. Swanson, 1966, "Further Studies of Denver Air Pollution", Dept. of Atmospheric Science, Colorado State Univ. ASP #105.

"Air Pollution in the Denver Area", 1967, pamphlet published by Public Service Company of Colorado, text prepared by L.W. Crow, Consulting Meteorologist.

Riehl, H., D. Herkhof, 1970, "Weather Factors in Denver Air Pollution", An abridged version of the final report to the U.S. Dept. of Health, Education and Welfare, Dept. of Atmospheric Science, Colorado State Univ. ASP #158.

DATA SOURCES AND THEIR LOCATION

The geographic area of greatest concern for air pollution in the Denver metropolitan area is primarily a segment of the Platte River drainage extending from a few miles south-southwest to a few miles north-northeast of the city center. The map shown as Fig. 1 identifies most of the data collection points used in this study. The area shown covers approximately 25 miles square. The Atomic Energy Commission"s facility at Rocky Flats, which is operated by Dow Chemical Company, is located at the northwest corner of the map. The town of Henderson is near the northeast corner and the Arapahoe County Airport is near the southeast corner.

Two elevation contour lines, one at 5200 feet and the other at 5500 feet, indicate the downward slope of the terrain on both shoulders of the Platte River drainage. Although not shown, a 6000 foot contour line runs near the west edge of the map. There is a minor drainage basin along Sand Creek, which runs from just west of Buckley Air National Guard Base (ANGB) toward the northwest past Stapleton. The surrounding terrain features help influence wind directions within that small drainage basin. Also, the combination of Clear Creek which drains from the mountains near Golden toward the northeast, and Ralston Creek which drains from the northwest toward Arvada, helps influence local windflow patterns in that portion of the metropolitan area.

The locations where pibals were released are identified at the cross points in the seven point vertical scales at Arvada, Yellow Cab, and the EPA Trailer site. The major highways and thoroughfares which are shown carry a major portion of the automobile traffic in the metropolitan area.

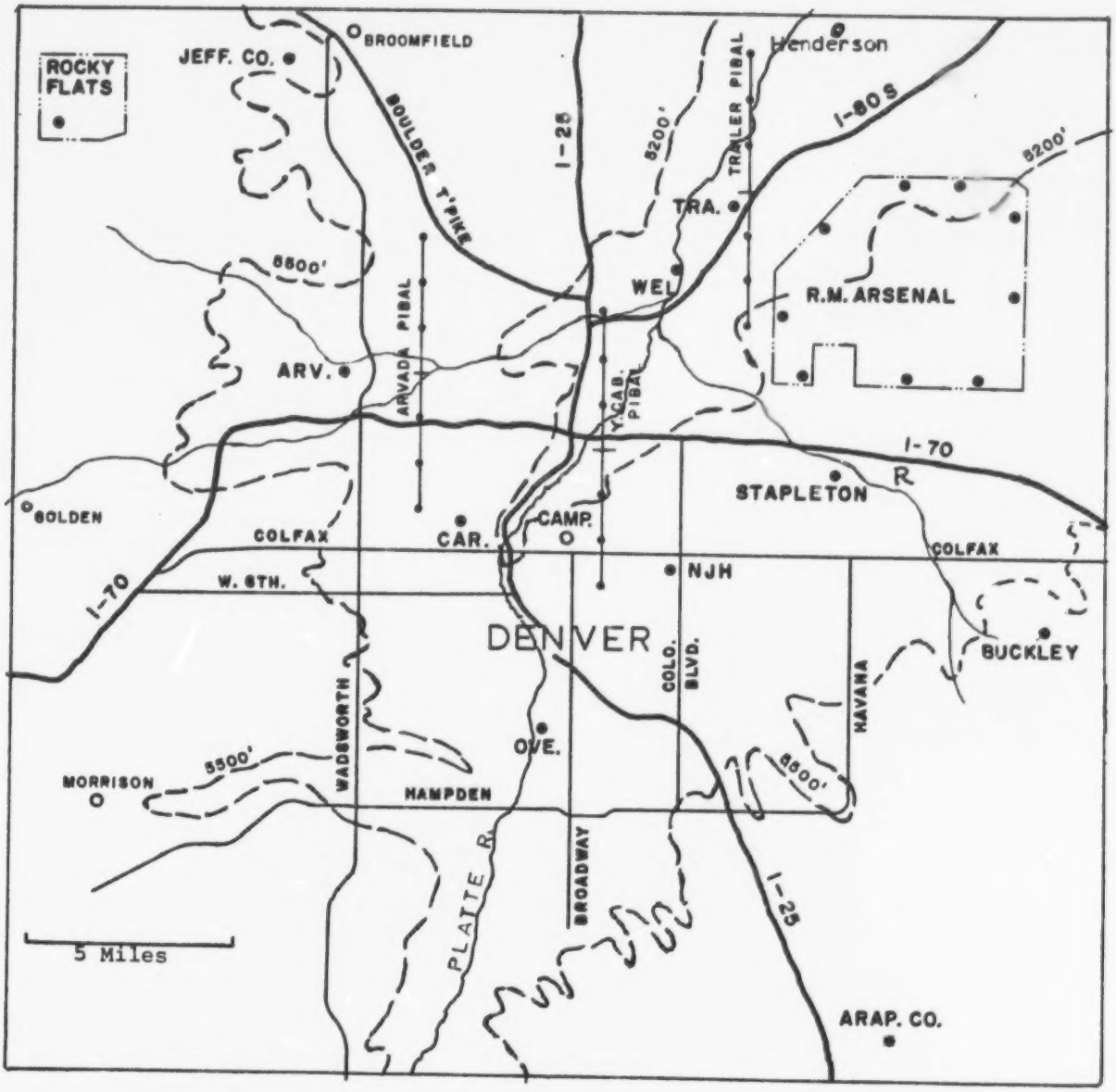


Figure 1. Identification map.

Since early 1965 Denver has been one of the cities where air pollutants are being measured in the Continuous Air Monitoring Program (CAMP). Denver's station is located at 2105 Broadway.

The types and frequency of observations and photographs collected are indicated in Table I.

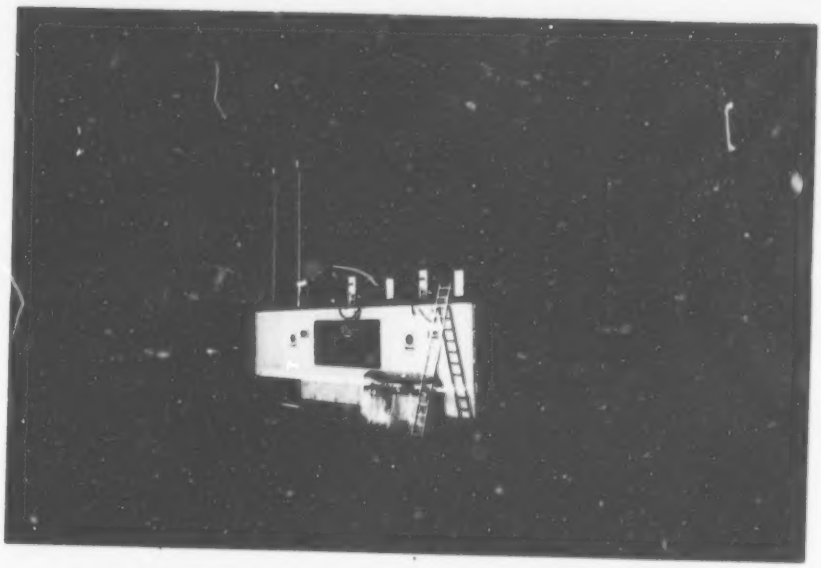
The Environmental Protection Agency operated aerosol sensing equipment in a trailer unit shown in Fig. 2. This trailer was located just north of 88th Street and to the west of Highway 80S in the northeast portion of the metropolitan area.

An example of the type of sensing station, including wind measuring equipment operated by the Colorado State Department of Public Health, is illustrated by Overland Golf Course station shown in Fig. 3.

The location of the theodolite at the Yellow Cab Headquarters with two faithful observers holding balloons ready for release is shown in Fig. 4.

TABLE I. DATA INDEX OF METEOROLOGICAL AND PHOTOGRAPHIC DOCUMENTATION COLLECTED FROM MULTIPLE SOURCES IN THE DENVER AREA BY LOREN W. CROW AS PART OF THE EPA AIR POLLUTION STUDY FOR NOVEMBER, 1973.

	Nov. 6	7	9	10	14	16	17	20	21	24	29	30
PIBALS												
EPA Trailer (# runs--	6	6		5	4	7	2		6	4		
Yellow Cab (0900 to	10	12	12	9	4	9	4		11	6		
Arvada (1500			12	9	5	13	4		11	7		
RAWINSONDES												
Stapleton AP # runs	2	a.m. only	3	a.m. only	2	2	a.m. only	2	3	2	2	2
SURFACE WINDS												
Airports # hours												
Stapleton 24	x	x	x	x	x	x	x	x	x	x	x	x
Buckley 24 plus	x	x	x	x	x	x	x	x	x	x	x	x
Jeff. Co. 17 temps.	x	x	x	x	x	x	x	x	x	x	x	x
Arap. Co. 17	x	x	x	x	x	x	x	x	x	x	x	x
Rocky Flats 24	x	x	x	x	x	x	x	x	x	x	x	x
Arsenal 24 (set of 9)	x	x	x	x	x	x	x	x	x	x	x	x
State Health 24												
Welby	x	x	x	x	x	x	x	x	x	x	x	x
Arvada	x	x	x	x	x	x	x	x	x	x	x	x
CARIH	x	x	x	x	x	x	x	x	x	x	x	x
NJH	x	x	x	x	x	x	x	x	x	x	x	x
Overland	x	x	x	x	x	x	x	x	x	x	x	x
EPA Trailer (partial)	4	9	10	17	10	24	16		17	12		
PHOTOGRAPHS												
Aerial - 80 min. flights	1020-1140		1120-1240						1040-1200			
Time-lapse												
Fed. Center to NE	x	x	x		x	x		x	x		x	
Buckley to NW					x	x		x	x		x	x
35mm slides												
EPA Trailer 4 dirs.		x		x	x	x			x			
Rocky Flats 3 dirs.	x	x	x					x	x		x	x
Sheraton Hotel 2 dirs.			x		x	x	x		x		x	x
L. W. Crow Misc.	x	x		x		x	x	x	x	x	x	
SURFACE TEMPERATURES												
Various business firms	x	x	x		x	x	x	x	x	x	x	



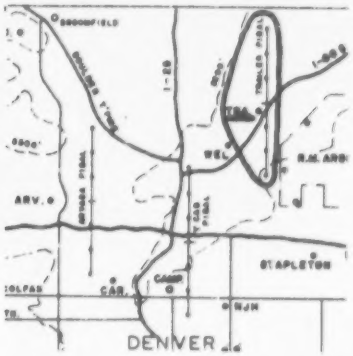


Fig. 2. Trailer operated by Environmental Protection Agency near I-80S and 88th St. Pilot balloon releases were also made here.

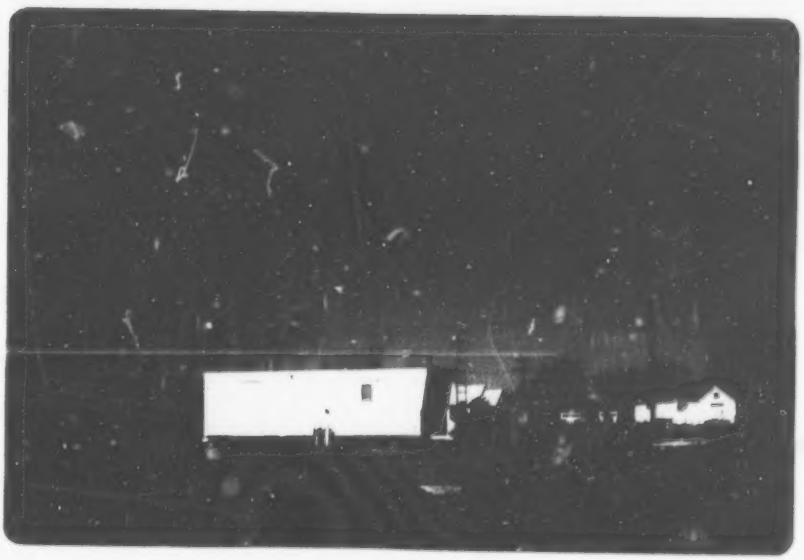


Fig. 3. One of 5 air sampling stations operated by Colo. Dept. of Public Health. This is Overland unit near Platte River and West Evans Ave.

Fig. 4. Pilot balloons ready for release and tracking at Yellow Cab site.

Reproduced from best available copy.

IMPORTANCE OF AIR STABILITY

The transport of air pollution, both from elevated sources, ground sources, line sources, and area sources, is highly dependent on the stability of the layer of air into which they are introduced. Fig. 5 shows a ribbon-like plume emanating from the Arapahoe Power Plant located south of the Overland station as viewed from the rawinsonde station at the east edge of Stapleton Airport facilities. Note that the plume moves several miles in a very limited vertical dimension at its effective stack height.

A compound plume of pollution can be formed by several individual elevated plumes. A similar compound plume can also be produced as a layer of pollution is raised above the ground level as it passes over the "heat island" of concentrated buildings and/or highways near the center of a city. Heat from the burning of 200,000 to 400,000 gallons of gasoline during daily rush hour traffic periods helps to expand the "heat island". An example of a "heat island" compound plume is shown in Fig. 6. The photograph was taken from I-70 just north of the rawinsonde station near 11 a.m.

During forenoon hours it is often possible to identify separate layers of pollution. A polluted layer of air having a local source near the ground can often be separated from an elevated plume by a non-polluted layer of clean air between. An example of this combination is shown in Fig. 7. This photograph was taken on October 25 looking directly northward from I-70 a few blocks east of its junction with Colorado Blvd. The scene illustrates how measurements made at the EPA Trailer during night and forenoon periods of stable air near the ground might be limited to very

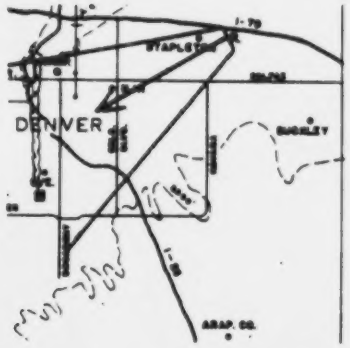


Fig. 5. Elevated plume from Arapahoe Power Plant moving horizontally in stable air as seen from rawinsonde station; 0900, Oct. 25, 1973.

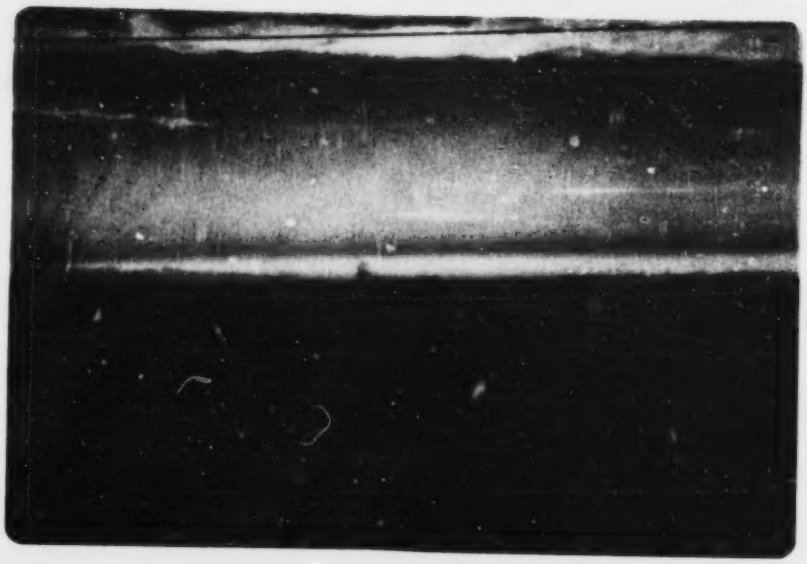


Fig. 6. Example of elevated compound plume moving northeast beyond downtown Denver as seen from I-70 north of rawinsonde station; 1100, Oct. 25.

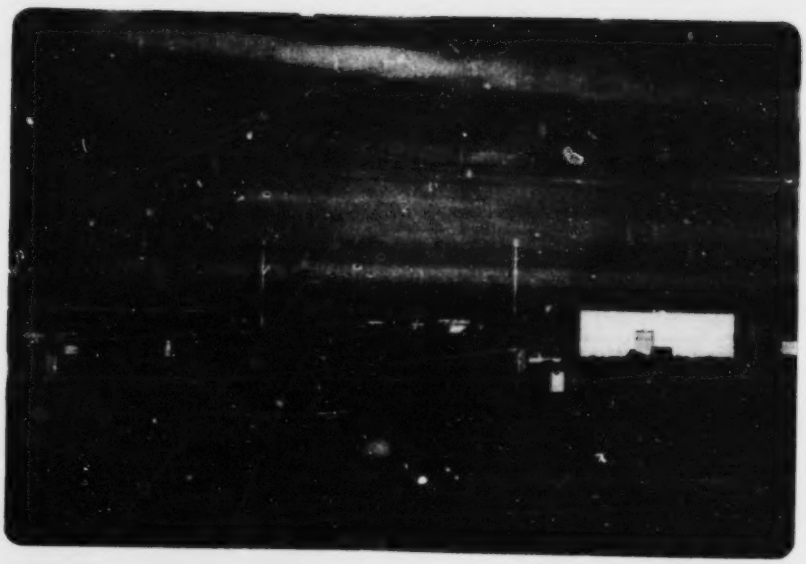


Fig. 7. Two layers of pollution, one at the ground and one elevated, northeast of downtown Denver as seen from I-70 and Cherry Street; 1115, Oct. 25.

Reproduced from best available copy.

localized ground sources. This could happen at the same time that a separate layer of more dense pollution might be moving away from Denver toward the north-northeast directly above the trailer.

Summaries of 12 morning temperature profiles from the 0500 Stapleton rawinsondes in the lowest 1500 feet are individually and collectively shown in Fig. 8. There were five two-day episodes during November for which considerable detailed data were collected - November 6-7, 9-10, 16-17, 20-21, and 29-30. In addition, there were two individual days - November 14 and 24.

Using an approximate composite of the 12 low level 5 a.m. soundings, the corresponding resultant patterns of pollution layers can be estimated. Three schematic diagrams which illustrate the influence of stability factors are shown in Fig. 9. Under stable air conditions each individual elevated plume moves off horizontally at its effective stack height with no mixing to the ground until surface heating is able to mix the layer up to and including the height range of that particular effective stack height above the terrain over which the plume has moved.

In Part B of Fig. 9, a comparative estimate is made of the temperature profile as it would occur within the heat island segment of air near the north edge of the downtown portion of the city. The influence of the heat island does not eliminate the air stability, but it can produce an elevated compound plume for materials moving farther downwind beyond the main portion of the heat island area.

In Part C of Fig. 9, indication is given as to how the top of a visible polluted layer emanating from ground sources increases as surface

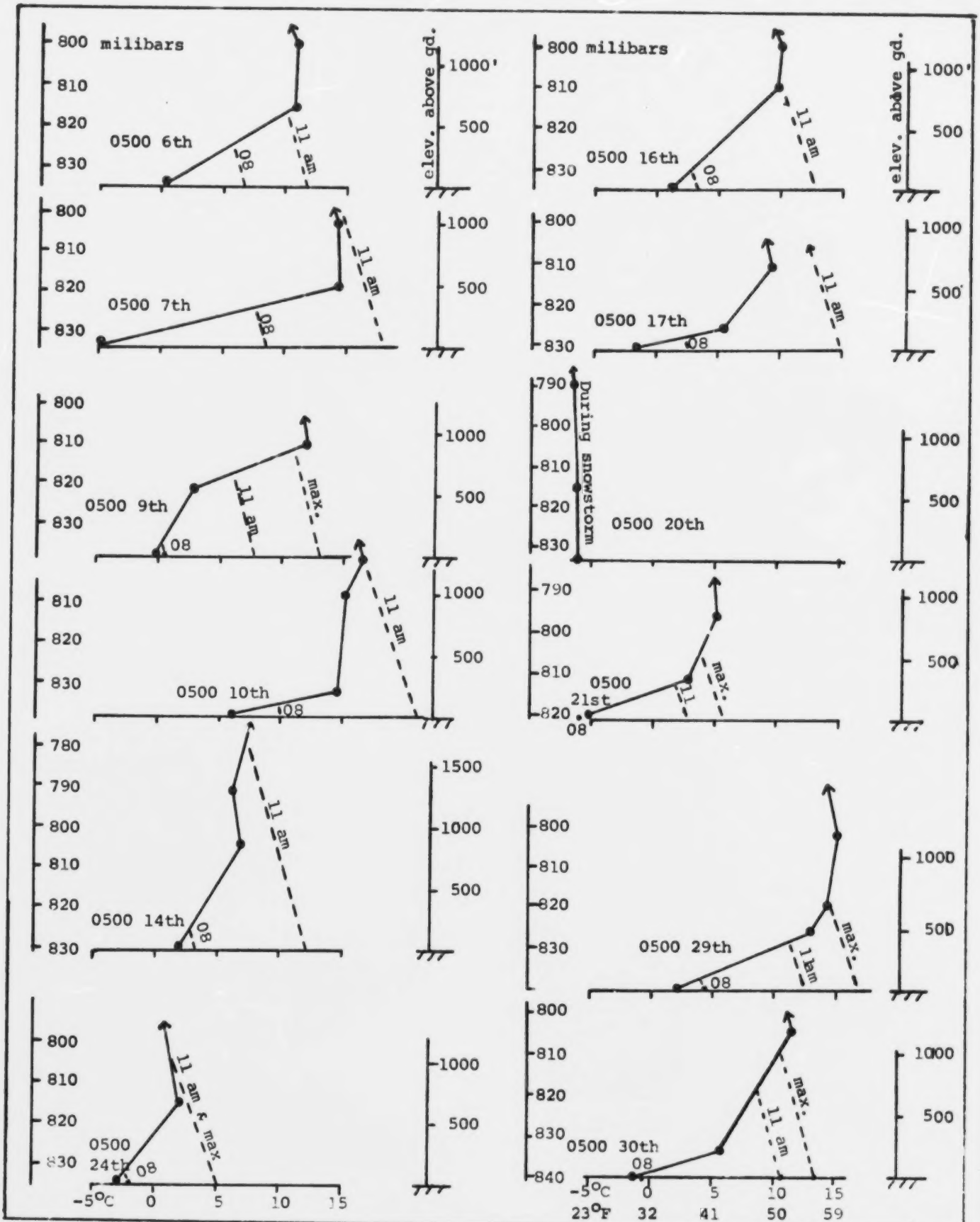
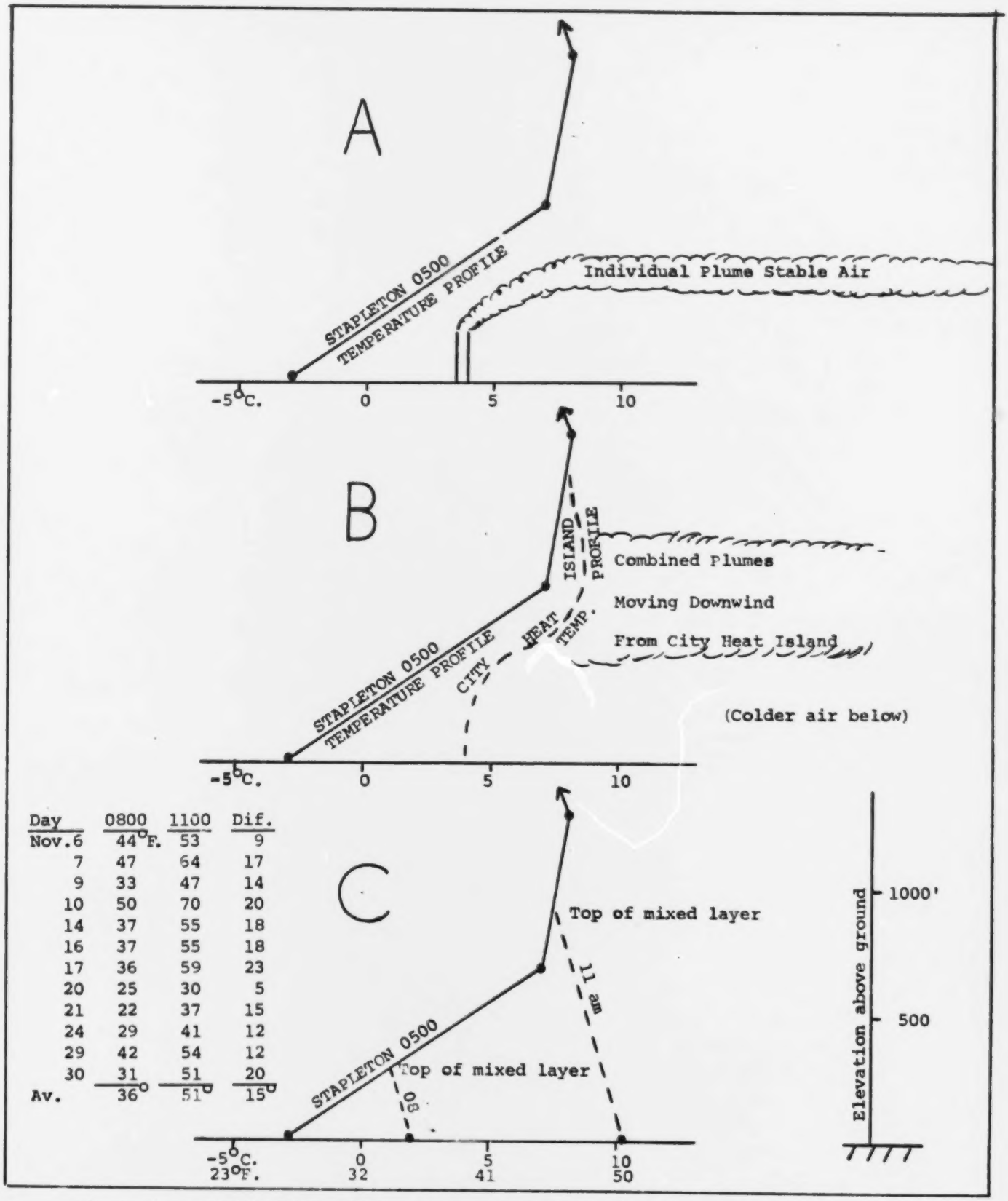


Figure 8. Early morning temperature profiles for 12 pollution episode days during November, 1973 as measured by rawinsonde at Stapleton Airport. Estimates of changes at 8 a.m. and 11 a.m. are based on surface hourly readings at Stapleton.



Day	0800	1100	Dif.
Nov. 6	44°F.	53	9
7	47	64	17
9	33	47	14
10	50	70	20
14	37	55	18
16	37	55	18
17	36	59	23
20	25	30	5
21	22	37	15
24	29	41	12
29	42	54	12
30	31	51	20
Av.	36°	51°	15°

Figure 9. Relationships of temperature profiles and polluted layers for: A. elevated source moving horizontally at effective stack height in stable air; B. city heat island effect producing elevated combined plume in stable air; C. comparative tops of polluted layer from ground level sources with increasing surface heating during forenoon hours.

temperatures increase during forenoon hours. However, when the air is mixed upward through sufficient depth to envelope elevated plumes separate layers can no longer be distinguished.

The nearly repeatable pattern of pollution over Denver on episode days is illustrated in the cross-section diagram of Fig. 10. This cross-section has been prepared to show the vertical profile of terrain and the pollution layer at various hours of the day as it is typically observed. The profile, which is greatly distorted in the vertical scale, runs from the mountainous area to the west-northwest of the Rocky Flats Plant southeastward to Buckley ANGB. This profile crosses the Platte River about three miles northeast of the downtown City of Denver and passes through Stapleton Airport. Multiple photographs, taken during the special study period of November, 1973, and during other periods studied by this author, support the approximate elevations of the polluted layer tops as shown in the cross-section for the hours from 0800 through 1500. These depths of the polluted layer should be considered typical of days in which the temperature inversion is NOT broken. In the summer months the respective tops of the polluted layer may be slightly higher.

The ground level for most downtown buildings is approximately 5200 feet above mean sea level. The higher buildings extend slightly more than 400 feet above ground level. Thus, they extend approximately 270 feet above the runway elevation for Stapleton Airport, which is 5331 feet. The elevation of the polluted layer tops is shown as above ground level at Stapleton Airport since the surface temperatures used to help derive the elevation tops are those measured hourly at the airport. Temperature profiles from the 0500 rawinsonde at Stapleton have been used to support the findings shown in Fig. 10.

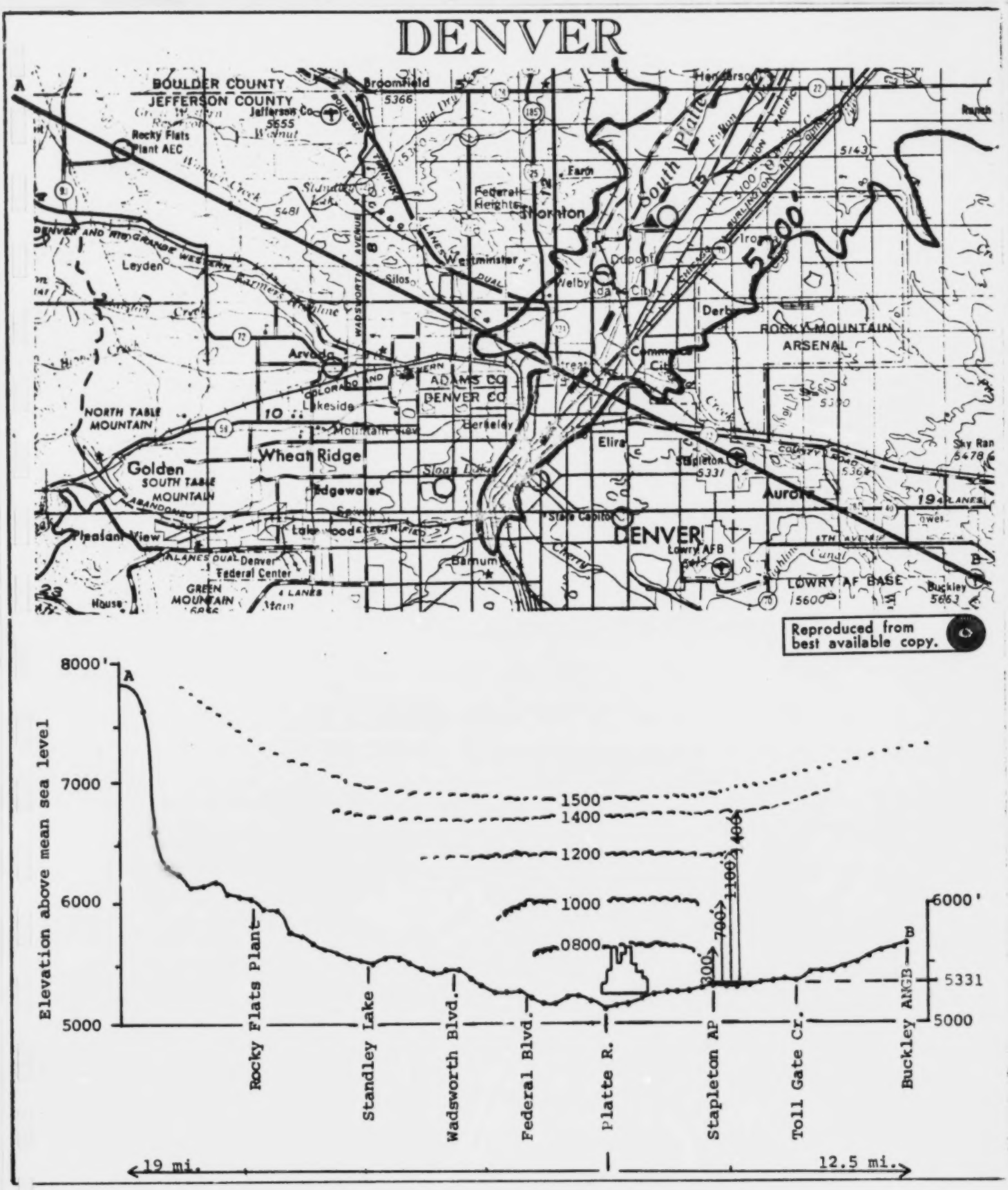


Figure 10. Typical WNW-ESE profile of pollution layer depths over metropolitan Denver between 0800 and 1500 on days when temperature inversions are not eliminated and when the polluted layer which forms near the downtown area spreads southward and away from its original location over the north edge of Colorado.

Although not shown in this cross-section the sequence of air motion changing from downslope to upslope between 0800 and 1500 must be considered in estimating the top of the polluted layer. The most frequent direction of smoke layers as seen by the weather observer at Stapleton Airport is to the southwest through north. There are relatively few instances when the observer indicates that either smoke or haze is observed in all directions from his point of observation.

The most frequent pattern of spreading for the pollution layer from noon through 1500 is to the south and/or west of the downtown area. This is aided by upslope motion above the higher terrain located in that direction from the city. For instance, North Table Mountain, South Table Mountain, and Green Mountain all extend above 6000 feet MSL. At the tops of these relatively flat protrusions the layer of stable air in early morning hours is very thin. Thus, a small amount of surface heating is required to eliminate the stable air layer. The stable layer is replaced by air which is well mixed vertically. In some instances a chimney-like airflow pattern is produced. Air which is heated and rises above the low foothills may move back toward the east <u>above</u> the temperature inversion over the valley. This upward motion of air above the higher terrain where the temperature inversion has been eliminated induces a movement of air coming first southward and then westward from the downtown area of Denver. Before it reaches the mountainous terrain, vertical mixing often has destroyed the temperature inversion, and the upper edge of the polluted layer becomes quite diffuse.

The top of the polluted layer is best characterized as having small undulations rather than being absolutely flat. An instantaneous photograph

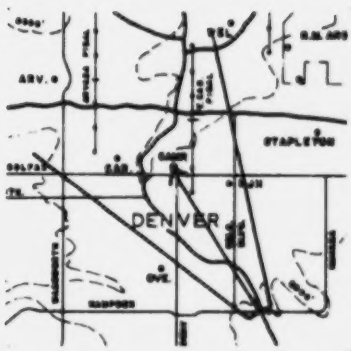
often makes it appear as quite level but time-lapse photography shows variations in the upper level.

The frequency with which the western edge of polluted layer reaches Rocky Flats is less than one-third of the days when relatively dense pollution can be noted in the downtown area of Denver. Likewise, there are very few instances when the polluted layer envelopes Buckley ANGB.

When a layer of pollution extends over the downtown area it correspondingly decreases the rate at which surface heating can be produced by solar radiation. Therefore, by the early afternoon hours it is generally true that the surface temperatures are cooler under the polluted layer than in the surrounding terrain where clearer air has permitted more rapid surface heating. Thus, the profile pattern of Fig. 10 shows the outer edges of pollution to be somewhat higher during afternoon hours. The higher ground surfaces above mean sea level near the outer rim of the basin, especially to the south and west of Denver, also help to support an earlier elimination of the temperature inversion with the same amount of solar radiation.

The contrast between clear days and days with heavy pollution over Denver is clearly related to variations in atmospheric conditions. The total input of pollutant material from all sources in the metropolitan area remains nearly constant during week days in any particular month of the year. Two photographs which show this contrast are presented in Fig. 11. Both photographs were taken where Hampden Blvd. crosses I-25 near the southeast edge of metropolitan Denver.

View of downtown Denver from 8 miles away at Valley Highway and Hampden Blvd.; 1225, Nov. 28.



View of downtown Denver enveloped in air pollution as seen from Valley Highway and Hampden Blvd.; 1030, Nov. 16

Reproduced from best available copy.

Figure 11. Contrast between nearly clean air and good visibility in downtown Denver on one weekday vs. polluted air and poor visibility on another weekday.

The upper photograph was taken at 1225 on November 28. The temperature at Stapleton Airport at 1153 was 57°. At 1253 it had risen to 62°. The minimum temperature near 6 a.m. had been only 29° but the layer of colder air near the ground had been eliminated between 1000 and 1100. The lower photograph made from the same point at 10:30 on November 16 shows a dense pollution layer less than 1000 feet thick over downtown Denver. The 5 a.m. temperature profile shown in Fig. 8 indicates that the temperature inversion was not eliminated by surface heating until well after 11 a.m.

A second difference between the two days was a linkage with synoptic airflow beginning at 10 a.m. on the 28th which rapidly moved most of the polluted air from the Denver metropolitan area eastward. This rapid west to east flow was not related to a particular frontal passage. Both days had little cloud cover.

DETAILED POLLUTION EPISODE PERIODS

The following episode periods have been examined to determine the airflow patterns both at the surface and through several hundred feet above the surface. The stability has been determined by temperature profiles obtained from the rawinsonde with some supplemental aircraft soundings. Individual hourly maps of surface winds have been prepared to show the high variability of airflow at different times for each day.

The wind record from pibal runs is shown for each hour that pibals were made. However, at both the Arvada and the Yellow Cab locations additional pibal runs were also made for nearly all one-half hour intervals. Each pibal at all three locations had a theodolite reading made at 150 foot intervals even though they are reported here at 300 foot intervals between 300 feet above the surface and 1800 feet above the surface.

The photographs used in this report to help identify the dimension of the polluted layer are a very small sampling of the many which were taken, both from the air and from various locations around the city.

Although not shown, time-lapse photographs were made for several episode days at two points in the city. One camera, using Super 8 film, took pictures from the 13th floor of the Bureau of Reclamation Building located near the west edge of the metropolitan area. The second camera, using 16 mm film, took pictures from the roof of a hanger located at Buckley ANGB.

EPISODE DAYS NOVEMBER 6 - 7

The morning of November 6 was typical of a weather situation following a major snowstorm in the Denver area. Temperatures were cold near the snow covered ground surface and warmer above. There was a reversal of airflow on the afternoon of the 6th. The temperature inversion was not eliminated and the early morning hours of November 7 continued with a notable temperature inversion. This inversion was broken on the 7th and the polluted layer was moved away from the city by early afternoon. Detailed information on the polluted layer and the airflow pattern is given by photographs, hourly maps, and pibals shown in Figs. 12 through 18.

The three photographs in Fig. 12 confirm that the layer of pollution increased in height and moved southward and westward during afternoon hours. The hourly airflow pattern on the 6th and 7th shows downslope flow through 9 a.m. on the 6th and through 10 a.m. on the 7th. See Figs. 13 and 14. The 0500 temperature sounding and corresponding winds for the surface and three levels above the surface are shown at the appropriate hour. There was an "apparent frontal passage" indicated by the Stapleton observer at 1437 on November 7. Somewhat stronger northerly winds then interrupted the otherwise typical flow pattern for an air pollution day.

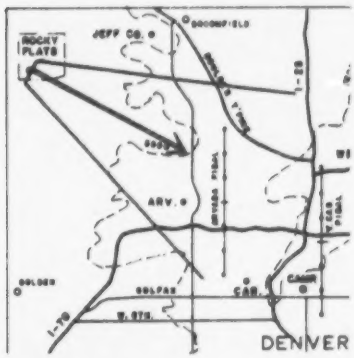
The 13 station sequence for which same-hour winds have been plotte. is shown in Fig. 15. The first six stations are on the left shoulder of the Platte River with the Overland and Welby stations being very near the river. Only three of the nine observation points within the Rocky Mountain Arsenal are listed. The seven stations on the right shoulders are arranged sequentially from lowest toward highest elevations.

Same-hour observations for both November 6 and November 7 are shown for 13 stations in Fig. 16. Some lines of demarcation are made at approximately the times when the air motion changes were greatest. Through 9 a.m. the data from all stations from Arvada through Arapahoe County Airport indicate downslope drainage of stable air. A near reversal of airflow takes place at the lowest elevation first and gradually changes at stations with higher elevations on both shoulders of the river. The upslope motion initially is quite localized with the gradual change to a predominant northeast toward southwest flow in mid-afternoon hours. Drainage flow begins again on the 16th between 4 and 5 p.m. at most stations.

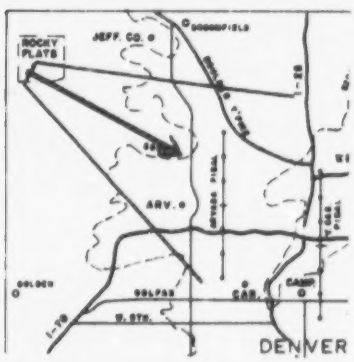
The wind observations at the Dow Chemical Plant at Rocky Flats and at the Jefferson County Airport indicate relatively independent patterns of airflow at these two stations on both the 6th and 7th.

Downslope drainage continued from late afternoon on the 6th into the morning of the 7th until late forenoon. This was followed by a definite valley-wide path of airflow from some easterly direction

Denver skyline from Valley Highway and 13th St. Layer top estimated between 400 and 500 ft. above ground; 0840, Nov. 6.



Pollution layer extending northeastward from Denver as seen from Rocky Flats. Note darkest portion of pollution is above ground; 1200, Nov. 6.



Same scene 3 hours later. Pollution layer is thicker and has moved to south and west; 1500, Nov. 6.

Reproduced from best available copy.

Figure 12. Progressive development with changes in depth, dimension, and location of pollution layer on November 6, 1973.

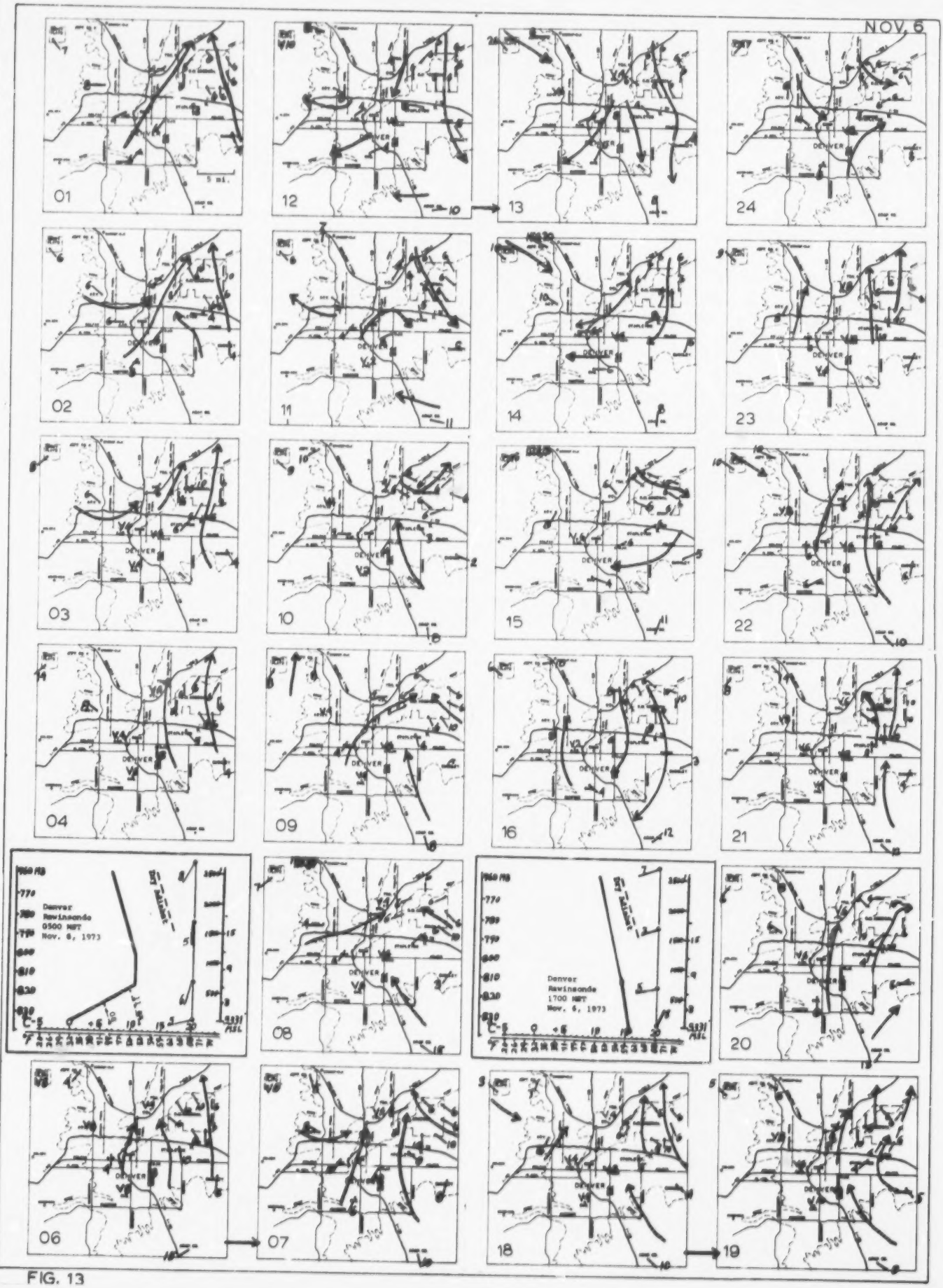

NOV. 6
01
12
13
24
02
11
14
23
03
10
15
22
04
09
16
21
Denver
Rawinsonde
0500 MST
Nov. 6, 1973
08
Denver
Rawinsonde
1700 MST
Nov. 6, 1973
20
06
07
18
19

FIG. 13

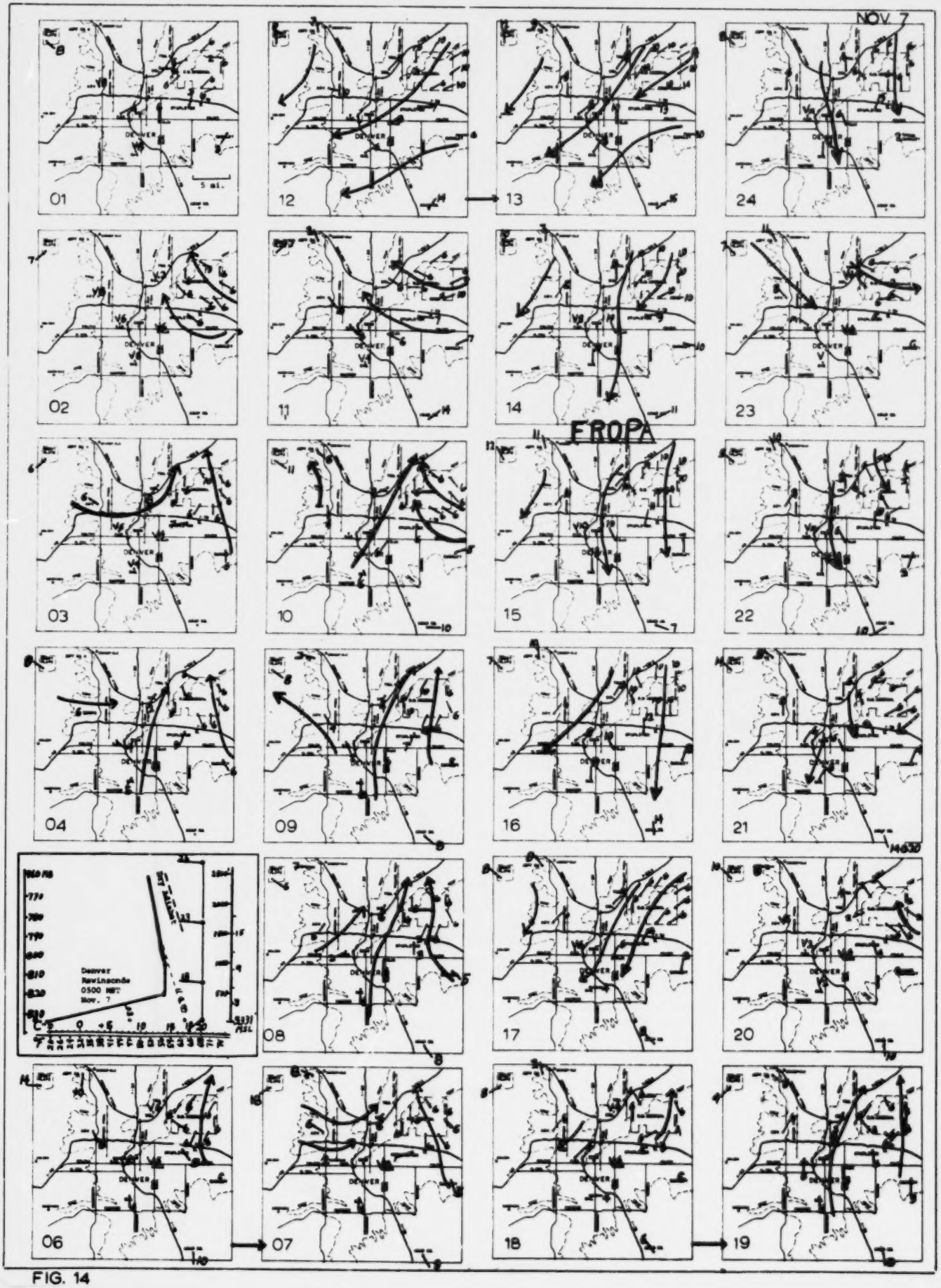

NOV. 7
01
12
13
24
02
11
14
23
FROPA
03
10
15
22
04
09
16
21
Denver
Rawinsonde
0500 MST
Nov. 7
08
17
20
06
07
18
19

FIG. 14

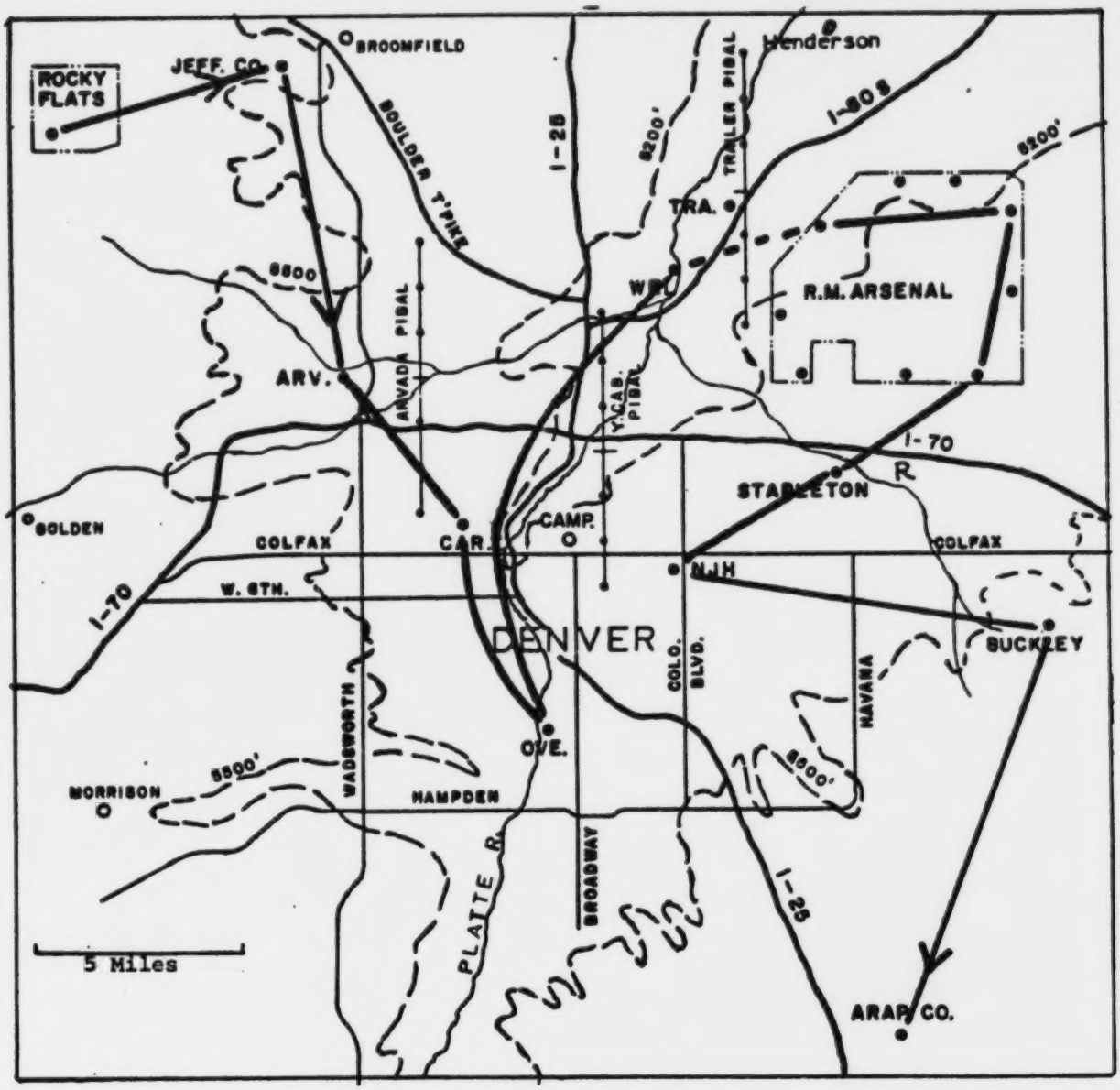


Figure 15. Sequential order of 13 wind measuring stations for which hourly data are presented in Figs. 16, 22, 27, 32, 39, 43 and 48. Sequence of stations goes generally from Rocky Flats down left shoulder across Platte River Valley and up right shoulder to Arapahoe County Airport.

Hourly temperatures in ^{o}F. at Stapleton are plotted to left of Stapleton winds. Relative humidity, if above 70%, is plotted to right of Stapleton winds.

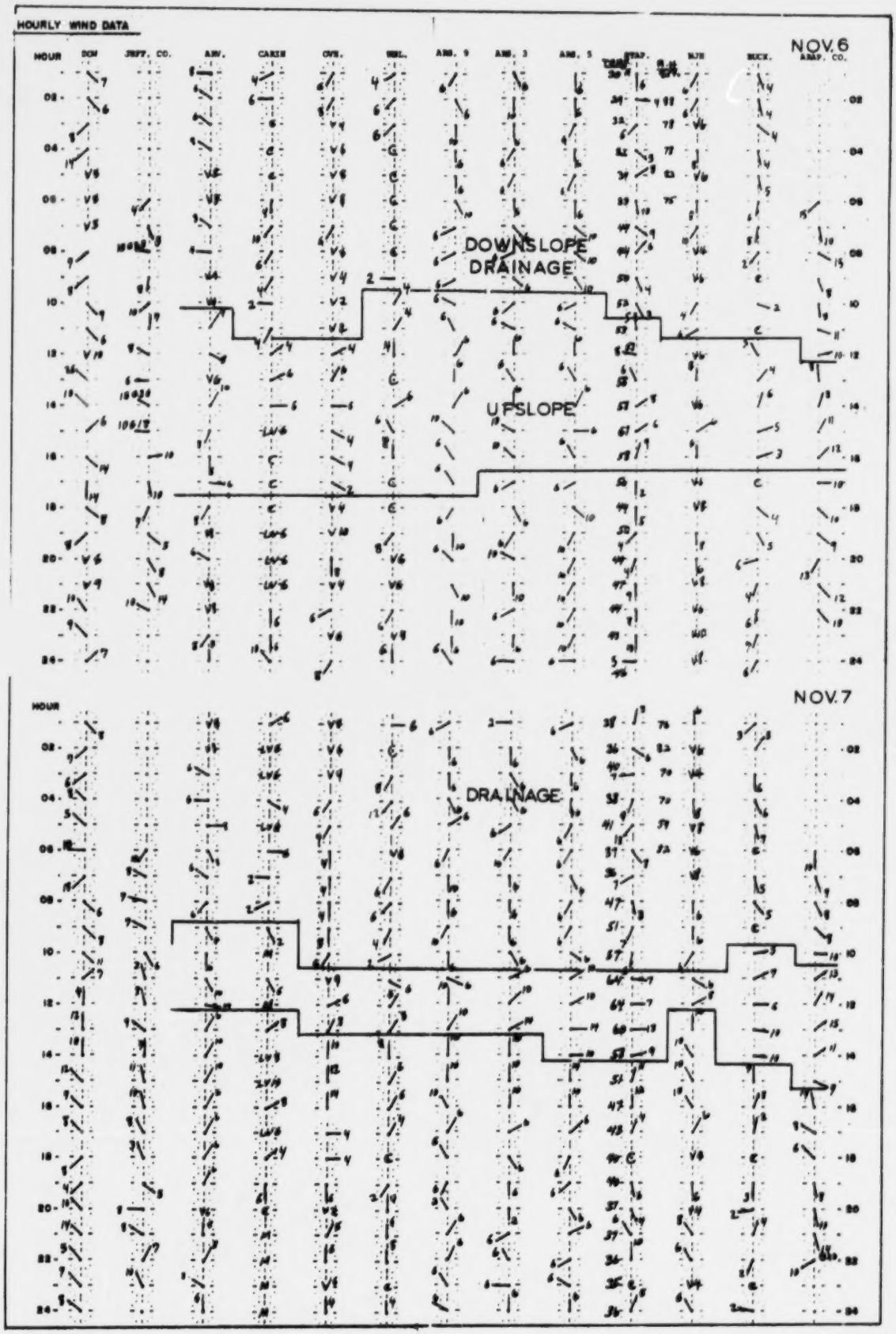

HOURLY WIND DATA
NOV. 6
HOUR
DOWNSLOPE
DRAINAGE
UPSLOPE
NOV. 7
HOUR
DRAINAGE

FIG. 16

until the approximate time of the "apparent frontal passage". After 1400 the winds show air moving from north to south across the entire valley.

The summarized information for all hourly pibal runs made on November 6 is shown in Fig. 17. The airflow above 900 feet remains westerly at the EPA Trailer throughout the entire day. Winds below 900 feet were from the east or northeast u til 1400. By contrast, there were almost no winds from a westerly component direction measured during the forenoon hours at the Yellow Cab station. Velocities were generally less than five knots. By 1500 the depth of airflow from the east or northeast extended to 1500 feet at Yellow Cab. At the same time synoptic airflow from the northwest enveloped all of the lower 1800 feet at the EPA Trailer.

The pibal runs at Yellow Cab and the EPA Trailer on November 7 are shown in Fig. 18. This shows a reversal of winds from the south, changing to a northeasterly flow at both stations between 10 a.m. and noon. Although the direction remained nearly the same, wind velocities increased beginning at 1300.

A time-lapse photographic record was collected at the Federal Center for both days.

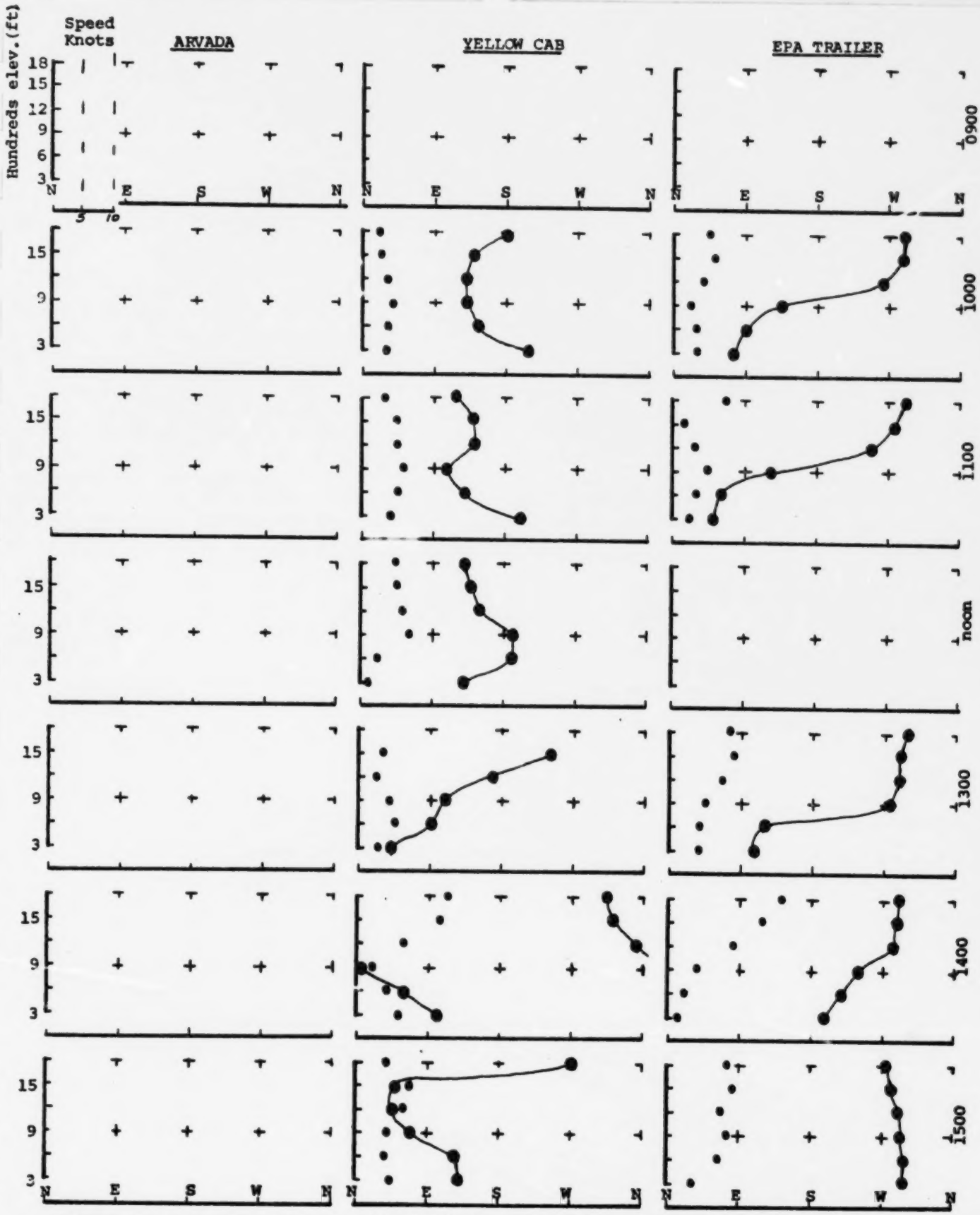


Figure 17. Sequential hourly pilot balloon runs showing wind speed and direction in lower 1800 feet, Nov. 6.

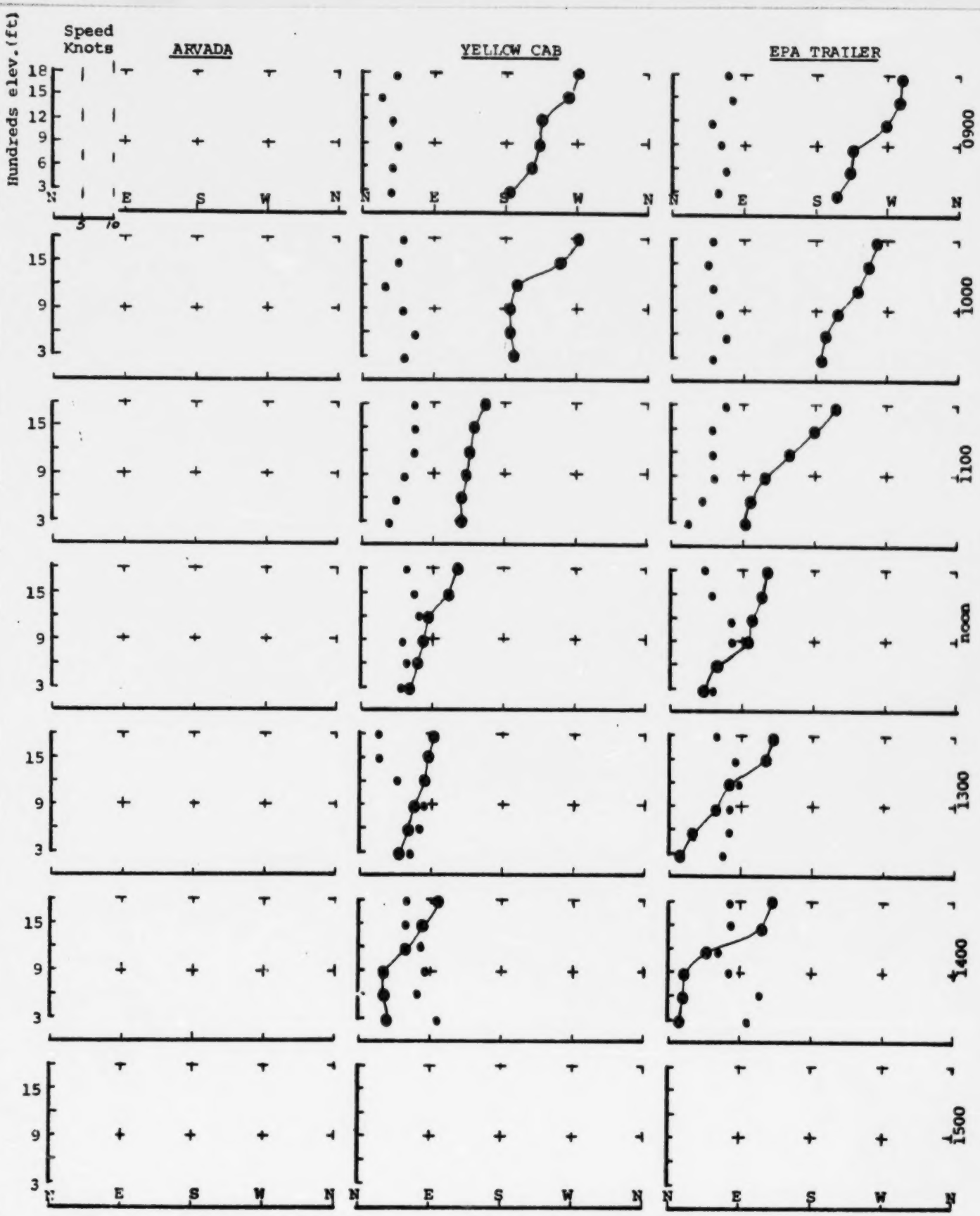


Figure 18. Sequential hourly pilot balloon runs showing wind speed and direction in lower 1800 feet, Nov. 7.

EPISODE DAYS NOVEMBER 9 - 10

There was patchy fog at 0800 hours throughout all of the metropolitan area on November 9. The temperature inversion was sustained beyond the time of the maximum temperature on that day. A rather shallow layer of cold air near the ground occurred in the early morning hours of the 10th. By 11 a.m. the temperature inversion was broken. Confirming photographs and windflow patterns are shown in Figs. 19 through 24.

The aerial photograph shown in Fig. 19 confirms a layer of relatively dense pollution covering most of the metropolitan area, particularly the central part of the city, near noon. Pikes Peak is visible in the background in the upper portion of the picture. The depth of the layer at this time was approximately 1100 feet over the central part of the city.

Hourly airflow charts covering the 9th and 10th are shown in Figs. 20 and 21. A confused, near calm condition is shown at most stations between 0400 and 0900 on the 9th. Air motion from northeast to southwest begins to dominate by 1000. On this day an extra rawinsonde was made near noon. The turn-around to drainage flow was nearly complete by 2000 hours on the 9th. This continued through approximately 11 a.m. The next day the drainage period was followed by an inversion breakup and linkage of the surface layers with the synoptic airflow, which was moving from northwest to southeast. See Fig. 21. By 1800 hours on the 10th drainage flow had set in, moving air downslope toward the bottom of the river valley at nearly all points.

The sequence of same-hour wind data at 13 stations shown in Fig. 22 reconfirms the pattern of reversal flow which occurred on November 9, the linkage with synoptic airflow for two to four hours at nearly all stations in early afternoon of the 10th, and the re-establishment of drainage flow by 1800 at ten of the 13 stations.

The pibal runs at two stations on the 9th and three stations on the 10th are shown in Figs. 23 and 24. Southerly flow aloft and northerly flow in the lower 900 feet for nearly all hours on the 9th prevailed. On the 10th the stable shallow layer moving air from south or east during the first three hours was eliminated between 1100 and 1200 at all stations except the EPA Trailer. By 1300 the strong synoptic flow was reflected at all three stations.

A time-lapse photographic record was collected at the Federal Center for Friday, November 9 but not for Saturday, November 10.

Reproduced from best available copy.

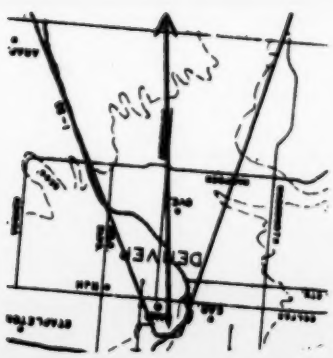


Figure 19. North to south aerial photograph from aircraft at 7000 ft. MSL near noon, Nov. 9. At 1200, Stapleton temperature was 54°, relative humidity was 52%.

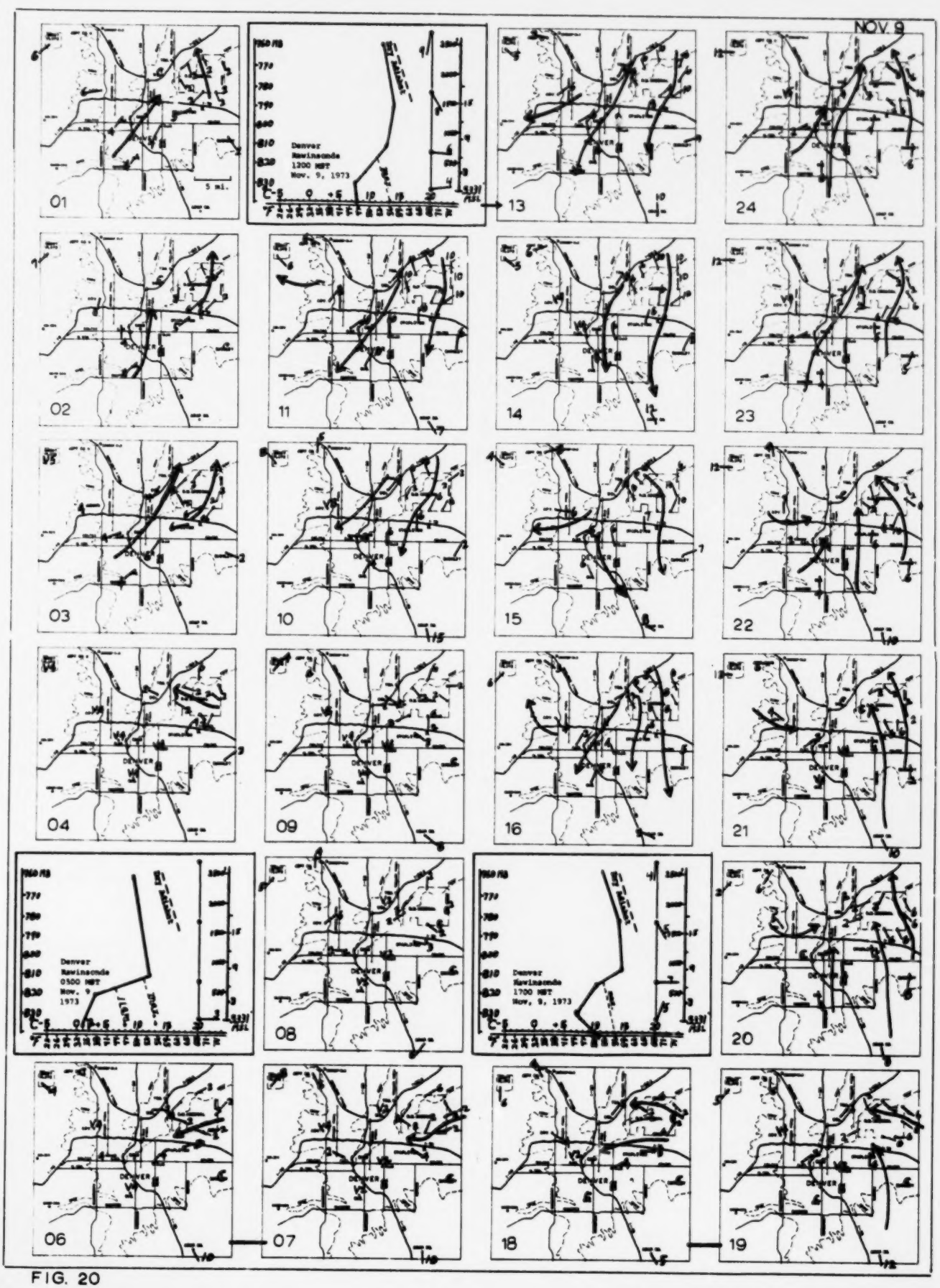

NOV. 9
01
02
03
04
05
06
07
08
09
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Denver
Kewlaando
1200 MST
Nov. 9, 1973
Denver
Kewlaando
0500 MST
Nov. 9
1973
Denver
Kewlaando
1700 MST
Nov. 9, 1973

FIG. 20

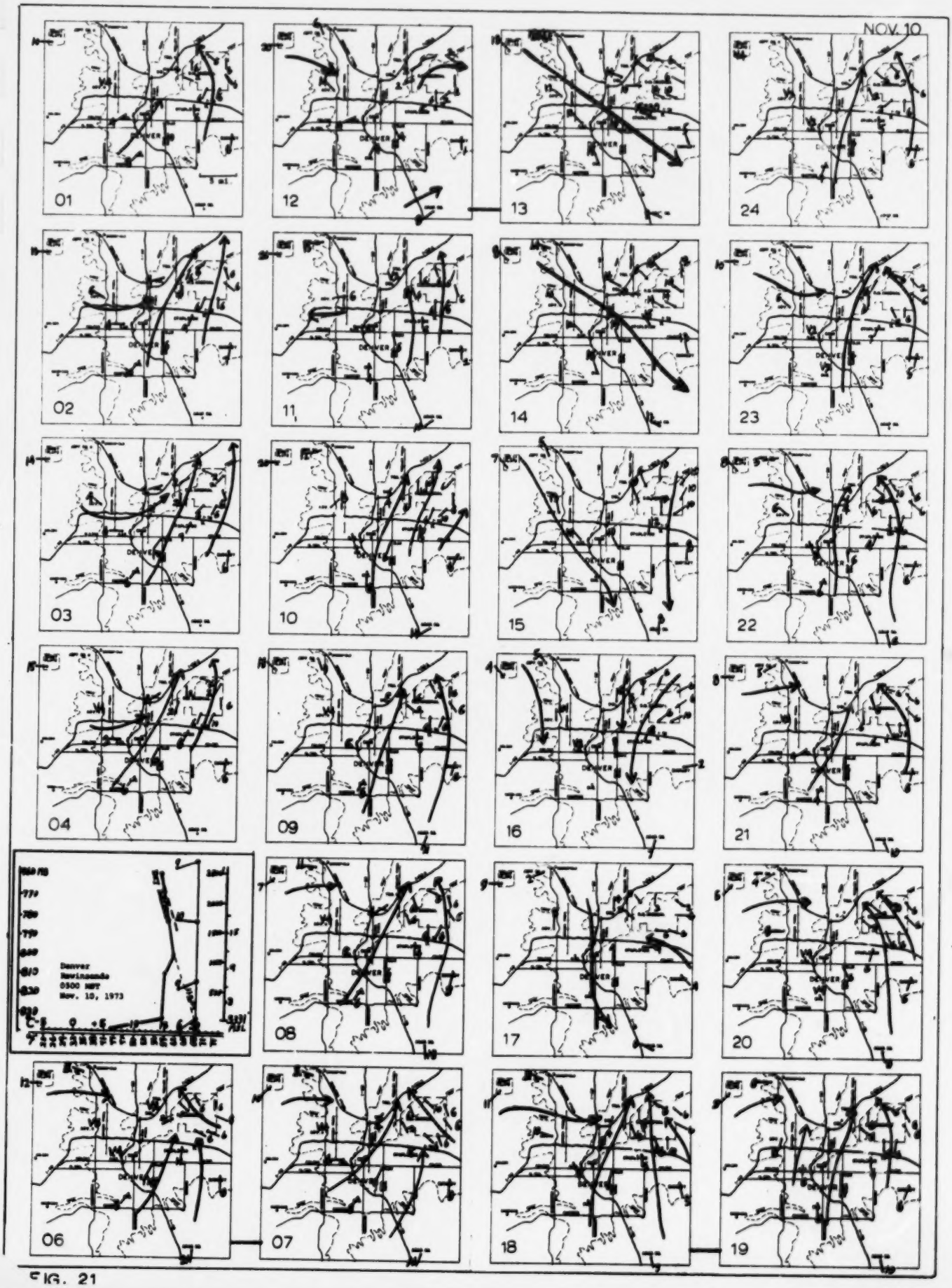

NOV. 10
01
12
13
24
02
11
14
23
03
10
15
22
04
09
16
21
Denver
Stapleton
0500 MST
Nov. 10, 1973
08
17
20
06
07
18
19

FIG. 21

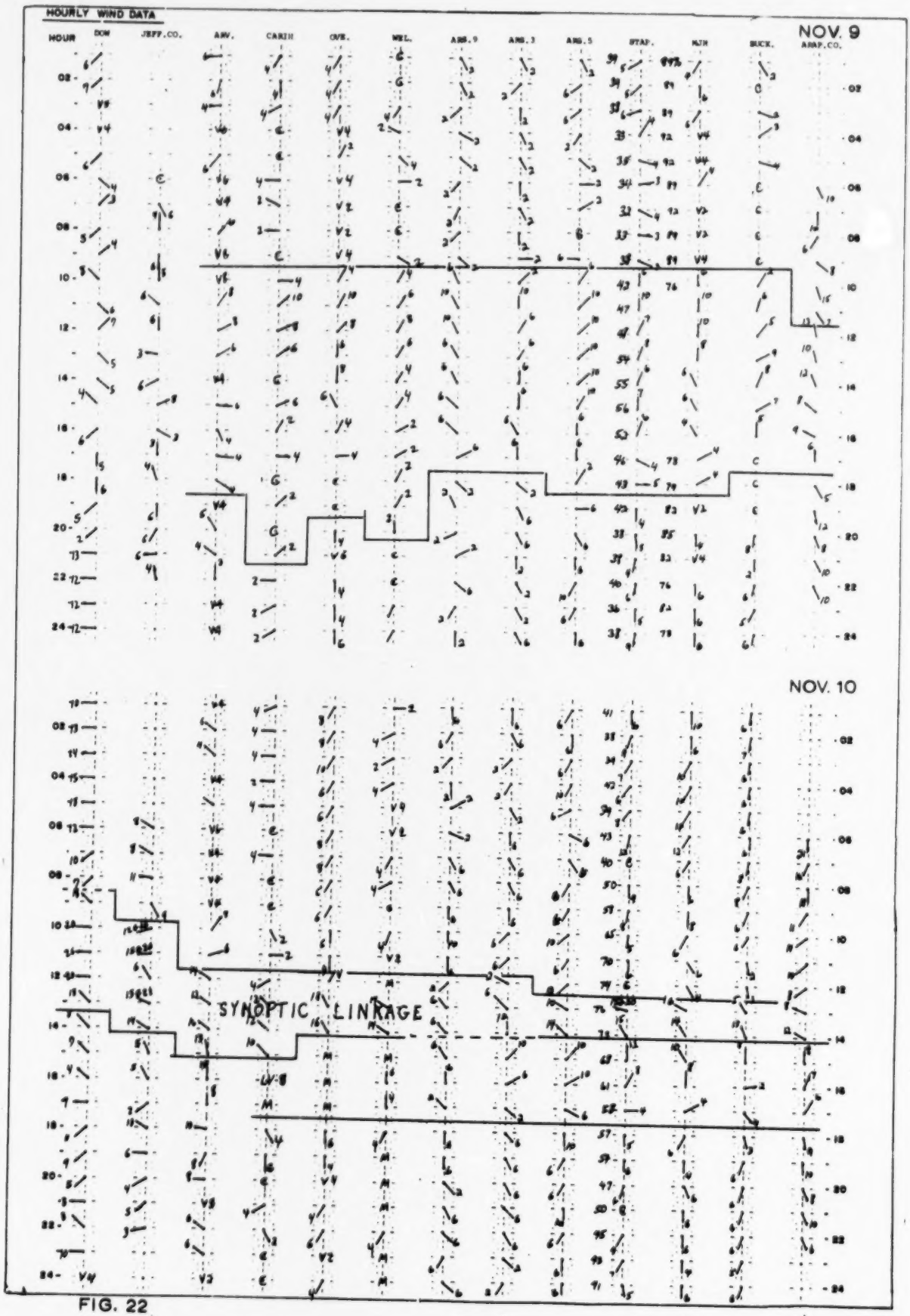

HOURLY WIND DATA
HOUR
DOM
JEFF.CO.
ARV.
CARIB
OVE.
WEL.
ARR.9
ARR.3
ARR.5
STAP.
KUH
BUCK.
ARAP.CO.
NOV. 9
NOV. 10
SYNOPTIC LINKAGE

FIG. 22

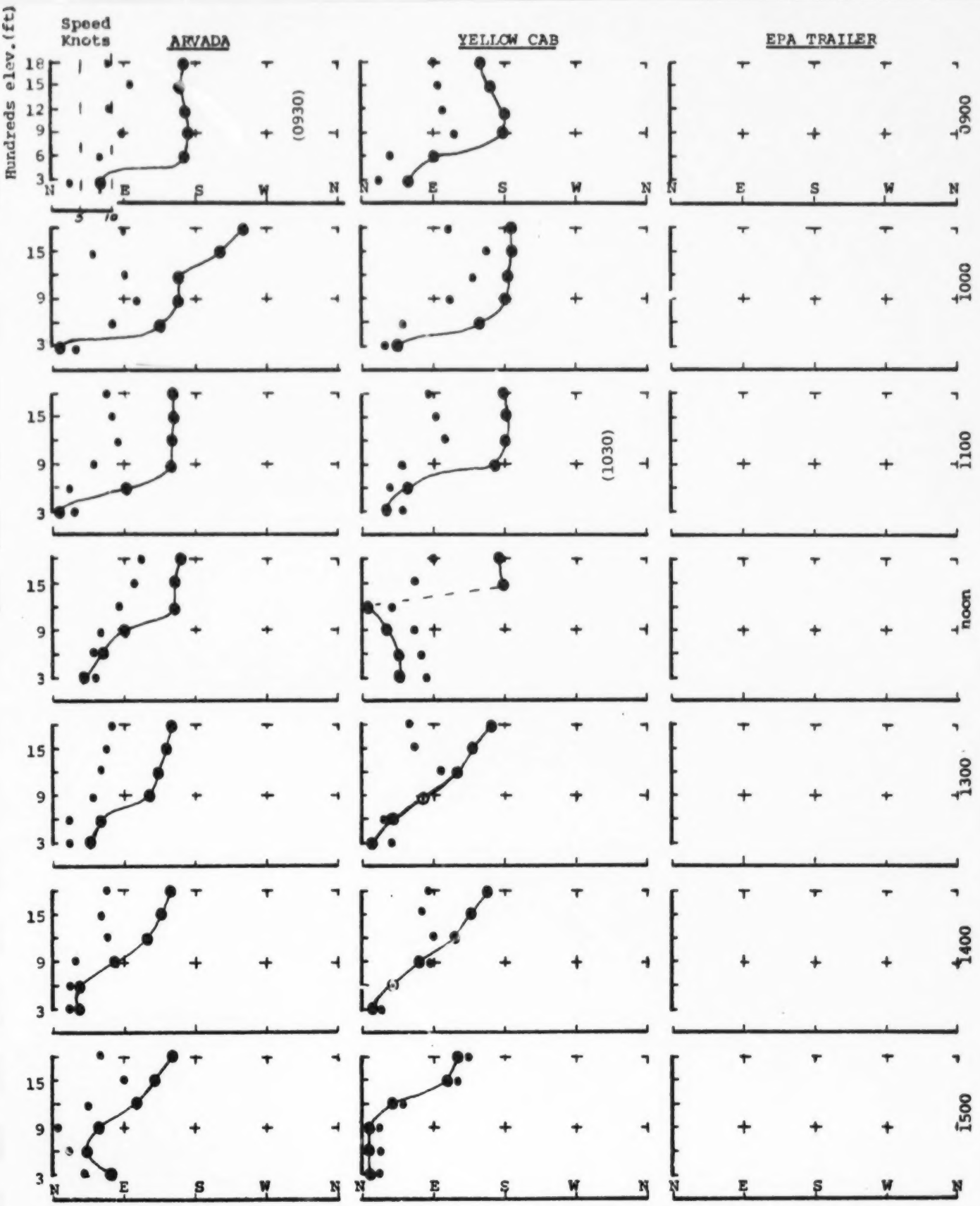


Figure 23. Sequential hourly pilot balloon runs showing wind speed and direction in lower 1800 feet, Nov. 9.

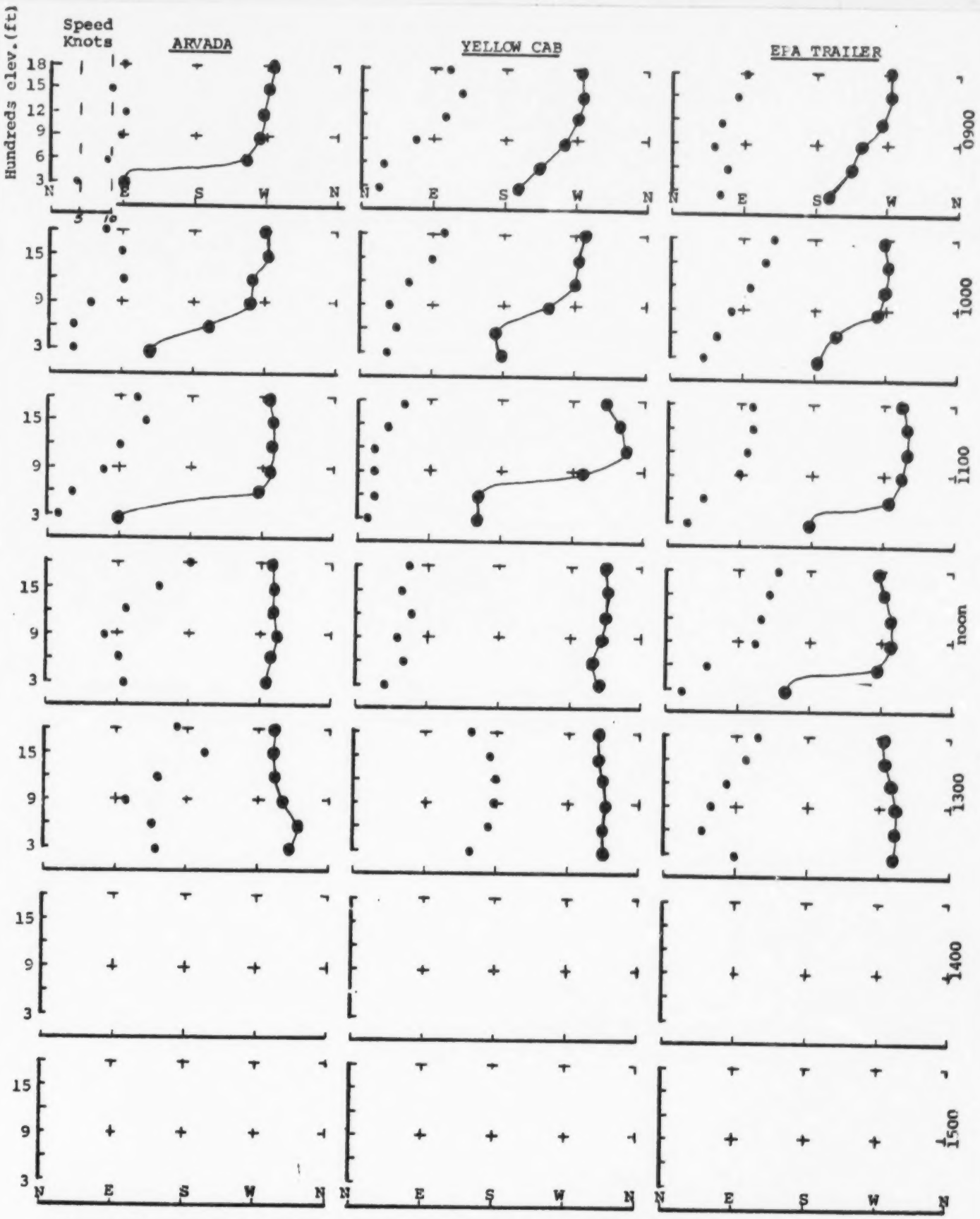


Figure 24. Sequential hourly pilot balloon runs showing wind speed and direction in lower 1800 feet, Nov. 10.

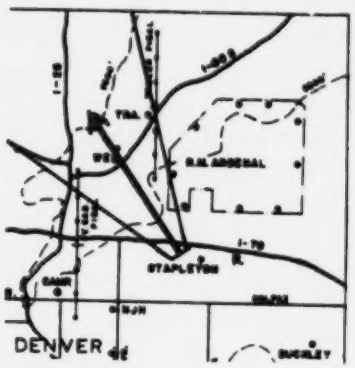
EPISODE DAY NOVEMBER 14

The day of the 14th was forecast to be a relatively light air pollution day. However, it was the first day that aircraft sampling facilities became available and wind measurements were made to fit with any aircraft measurements.

During the early forenoon hours the air pollution buildup was typical for a weekday morning. However, the temperature inversion which existed at 0500 was eliminated before noon and the layer of air near the surface was mixed with strong synoptic airflow from the west-northwest. The photographic record of this sharp change made from the observing site on the eighth floor of the Sheraton Inn-Denver Airport is shown in Fig. 25. The time-lapse photography at Buckley ANGB also confirms the rapid change which took place as the pollution layer was eliminated near noon.

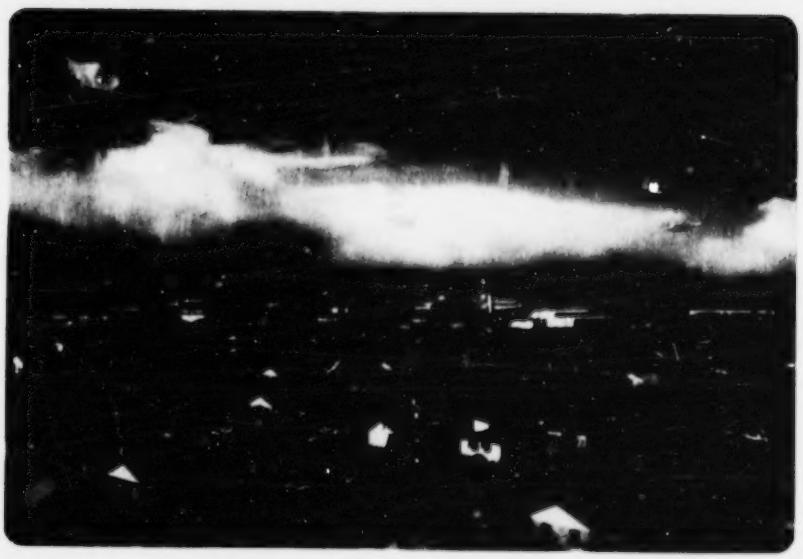
The hourly sequence of airflow patterns shown in Fig. 26 and the sequential hourly wind record in Fig. 27 show the abrupt change taking place between 1100 and 1200 at most stations. All of the hours from noon through midnight in Fig. 26 show a nearly constant flow pattern over the metropolitan area while strong winds prevailed.

The sequential hourly pibal runs shown in Fig. 28 indicate that winds from the west were measured at both Arvada and the Epa Trailer above 600 feet by 0900. By 1100 all three pibal stations had winds from the surface through 1800 feet from near west with the strongest velocities yet measured in the study period.



Layer of air pollution toward northwest from 8th floor of Sheraton Inn-Denver Airport; 0900, Nov. 14.

Reproduced from best available copy.



Same scene after pollution has been dispersed by strong westerly winds; 1200, Nov. 14.

Figure 25. Contrast between polluted air on a weekday morning and same scene at noon following one hour's linkage with synoptic airflow from west to east and elimination of the temperature inversion.

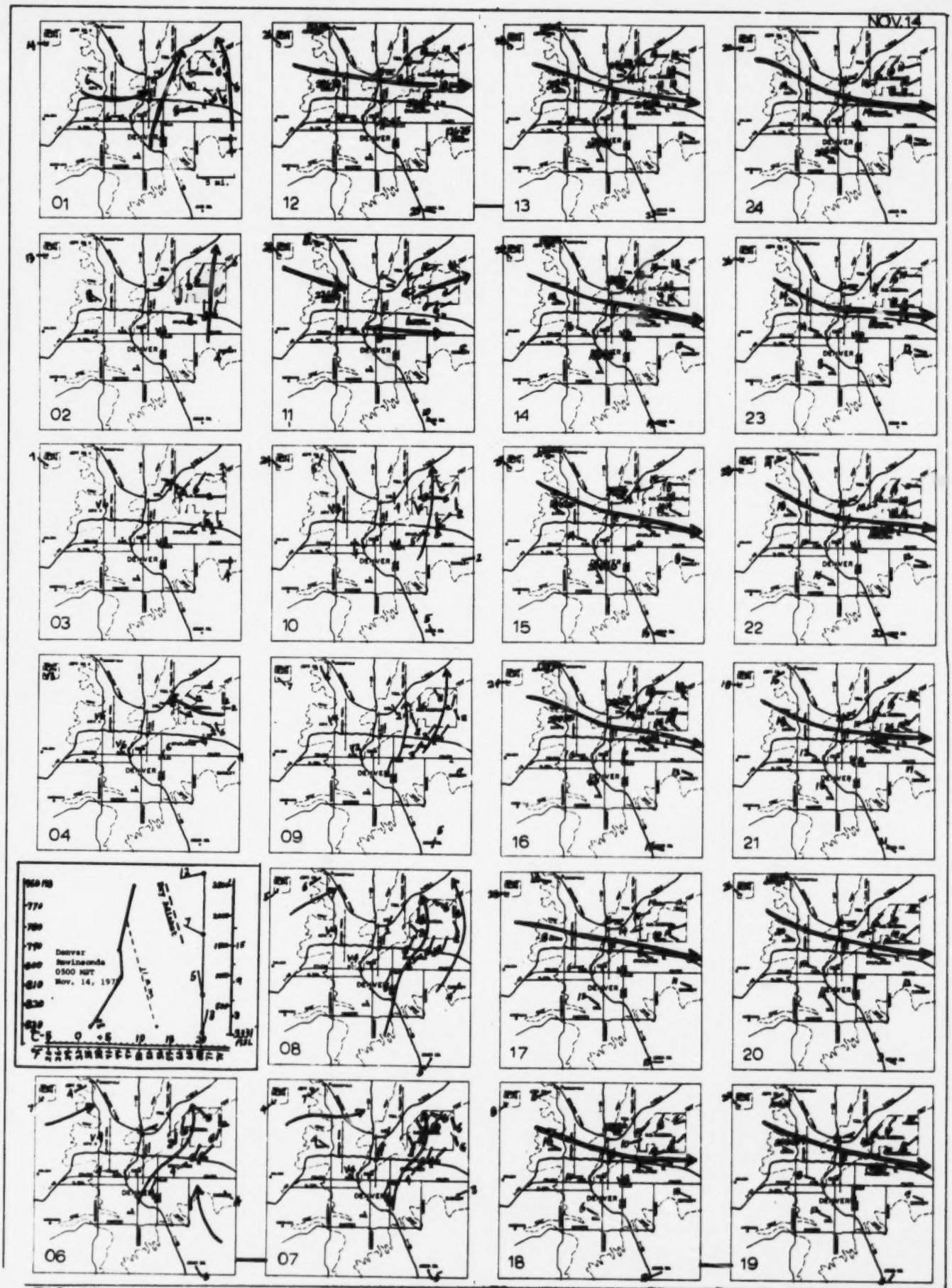

NOV.14
01
12
13
24
02
11
14
23
03
10
15
22
04
09
16
21
Denver
Rawinsonde
0500 MST
Nov. 14, 197
08
17
20
06
07
18
19

FIG. 26

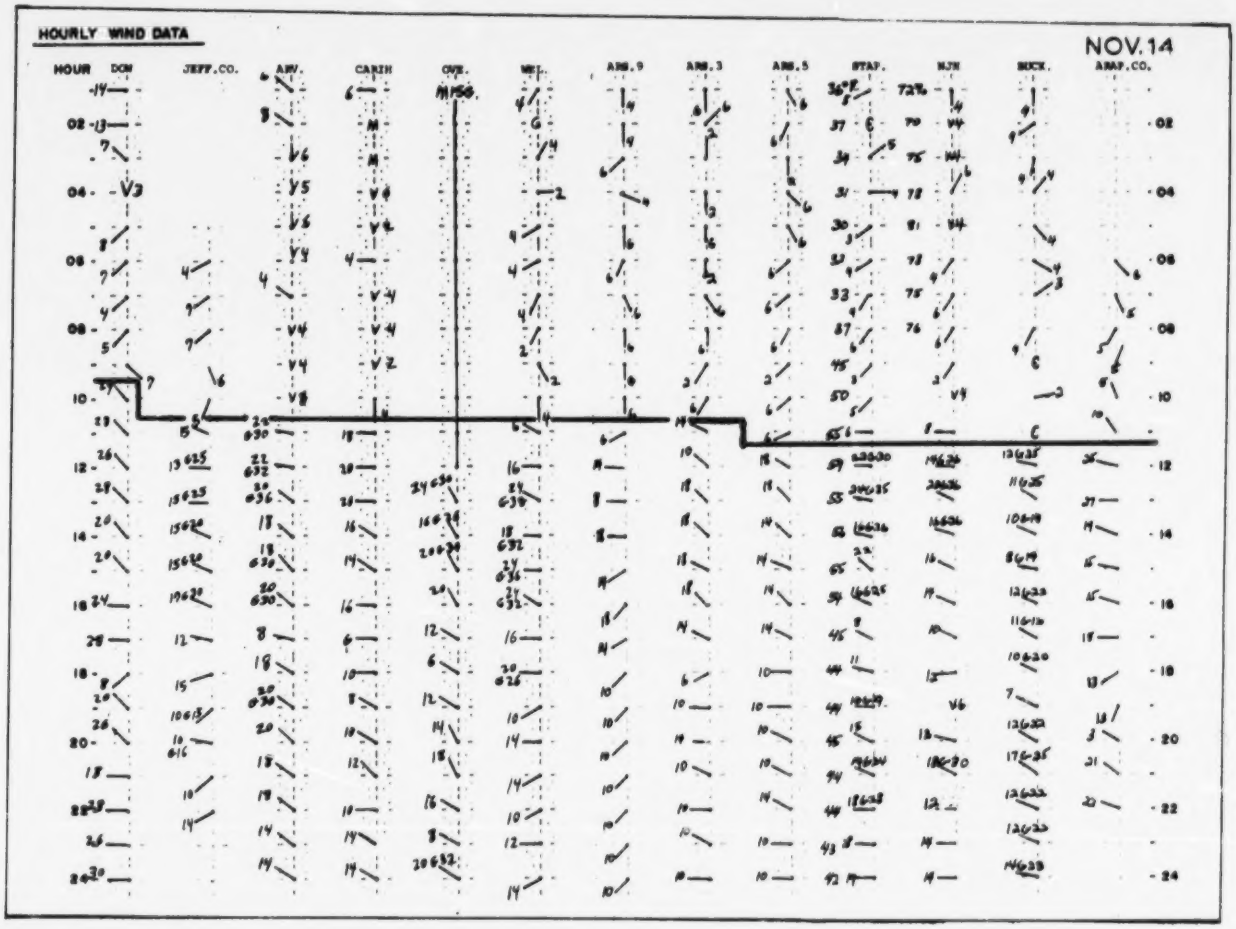

HOURLY WIND DATA
NOV. 14
HOUR
DCN
JEFF. CO.
ARV.
CARIB
OVE.
WES.
ARA. 9
ARA. 3
ARA. 5
STAP.
MJN
BUCK.
ARAP. CO.

FIG. 27

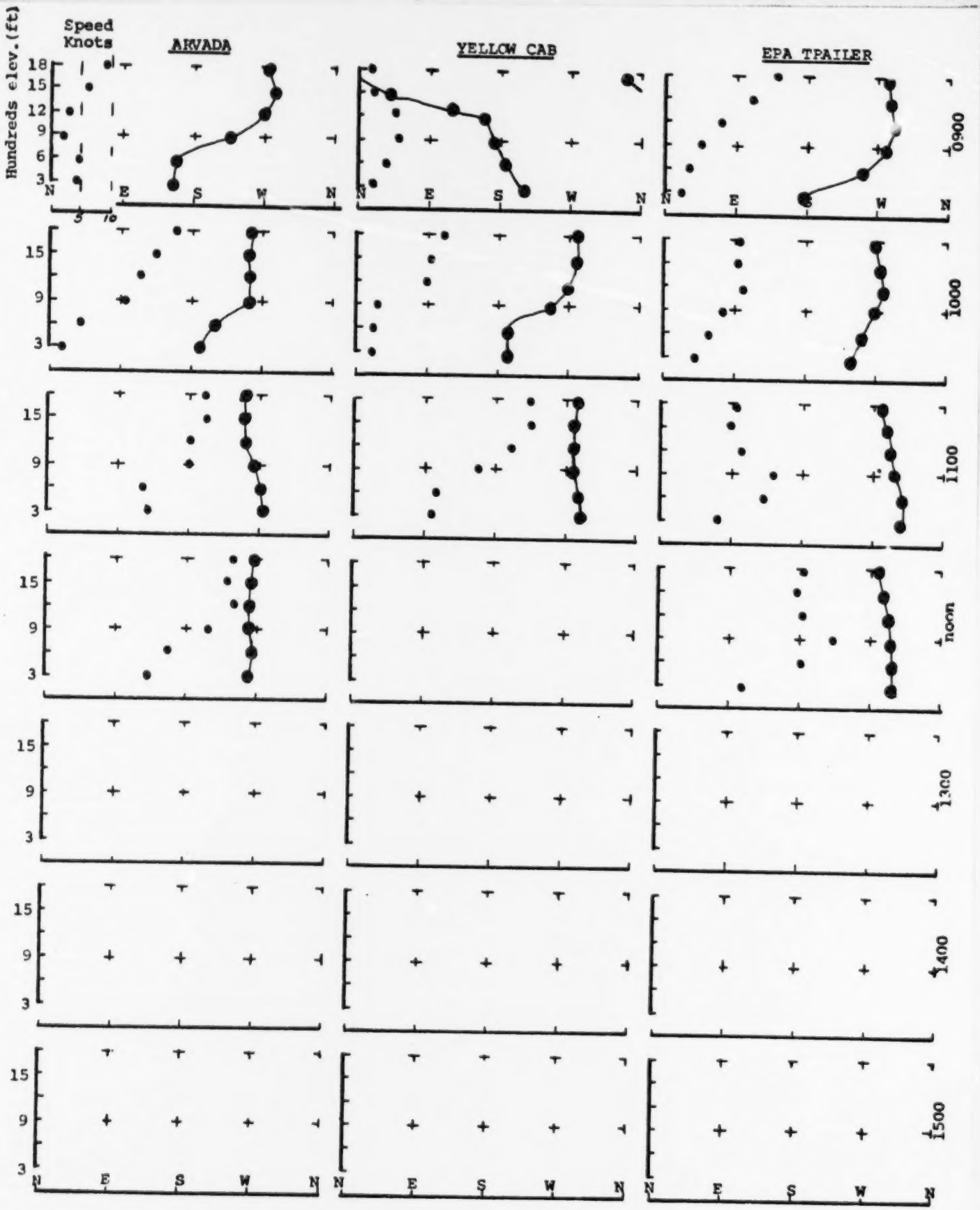


Figure 28. Sequential hourly pilot balloon runs showing wind speed and direction in lower 1800 feet, Nov. 14.

EPISODE DAYS NOVEMBER 16 - 17

The pollution episode for November 16-17 was primarily concentrated on Friday, the 16th. The airflow patterns showed a reversal from downslope to upslope occurring midforenoon on the 16th and a gradual thinning of pollution density during afternoon hours as the temperature inversion was eliminated.

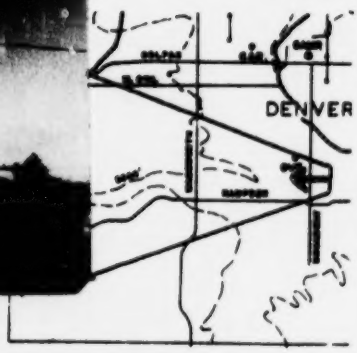
A sequential pattern of air pollution development beginning with stable air in the early forenoon hours is shown in Fig. 29. The plume emanating from the Arapahoe Power Plant is moving from south to north with almost no vertical mixing taking place once it reaches the effective stack height. There is an increase in the depth of the pollution layer with increased surface heating. This is confirmed by the photographs taken from the roof of the Park Lane Apartments.

The hourly airflow charts for the 16th and 17th are shown in Figs. 30 and 31. The flow of air in the early afternoon hours of the 16th moves the air from over the metropolitan area toward the nearest mountains to the west. This pattern of airflow is also shown in the upper portion of Fig. 32. The beginning of the flow from north to south starts first primarily at the lowest level stations at the north end of the metropolitan area. During late afternoon the airflow gradually changes from northeasterly to southeasterly for most stations on the right shoulder of the Platte River Valley. The airflow shifts around to a westerly component on the left shoulder of the valley near 1700 and 1800. Both the morning and evening changes of wind direction take place during period of low wind speeds.

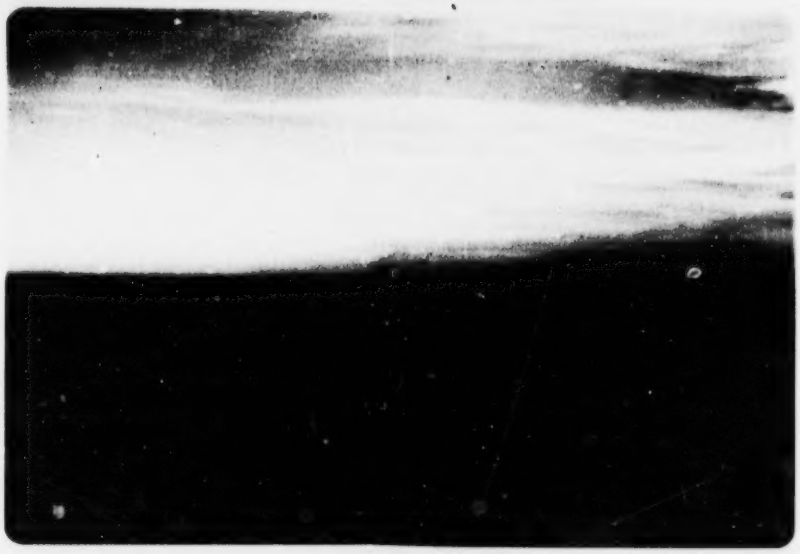
The nighttime drainage period between the 16th and 17th extended from near 1800 on the 16th through 1000 on the 17th. However, the surface temperature inversion was eliminated before 1100 on November 17. There was a three-hour period of synoptic linkage during the afternoon hours of November 17 when relatively strong westerly winds prevailed across the entire area. See Figs. 31 and 32.

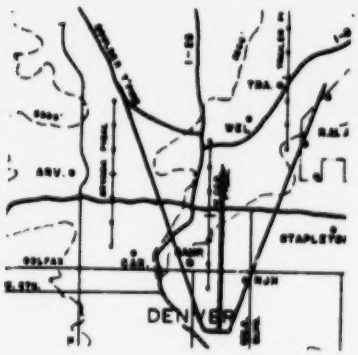
The pibal record for the 16th, shown in Fig. 33, illustrates the vertical profile of airflow as the layer of mixed air deepens. The shift in flow at levels above 600 feet from southwest to northeast is well documented. This is particularly notable between noon and 1300 at all three pibal stations.

There is little significance to the pibal record for Saturday, the 17th, shown in Fig. 34. The observers were instructed to stop all observations near 1100. No time-lapse photographs were made on the 17th.

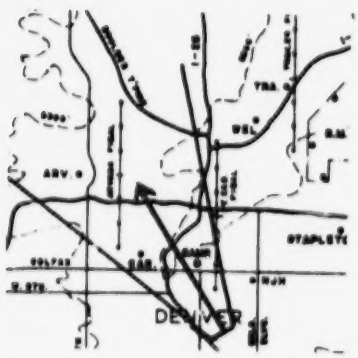


Plume from Arapahoe Power Plant moving south to north in stable air as seen from South Downing Street;
0805, Nov. 16





Multiple layers of pollution as seen to north from roof of Park Lane Apts.(200' elev.);
0840, Nov. 16



Scene to northwest from roof of Park Lane. Pollution layer mostly below 500 ft. in downtown area;
0840, Nov. 16

Reproduced from best available copy.

Figure 29. Confirming photographs identifying single elevated plume in south Denver and compound plume layers near north end of city, early forenoon hours, Nov. 16.

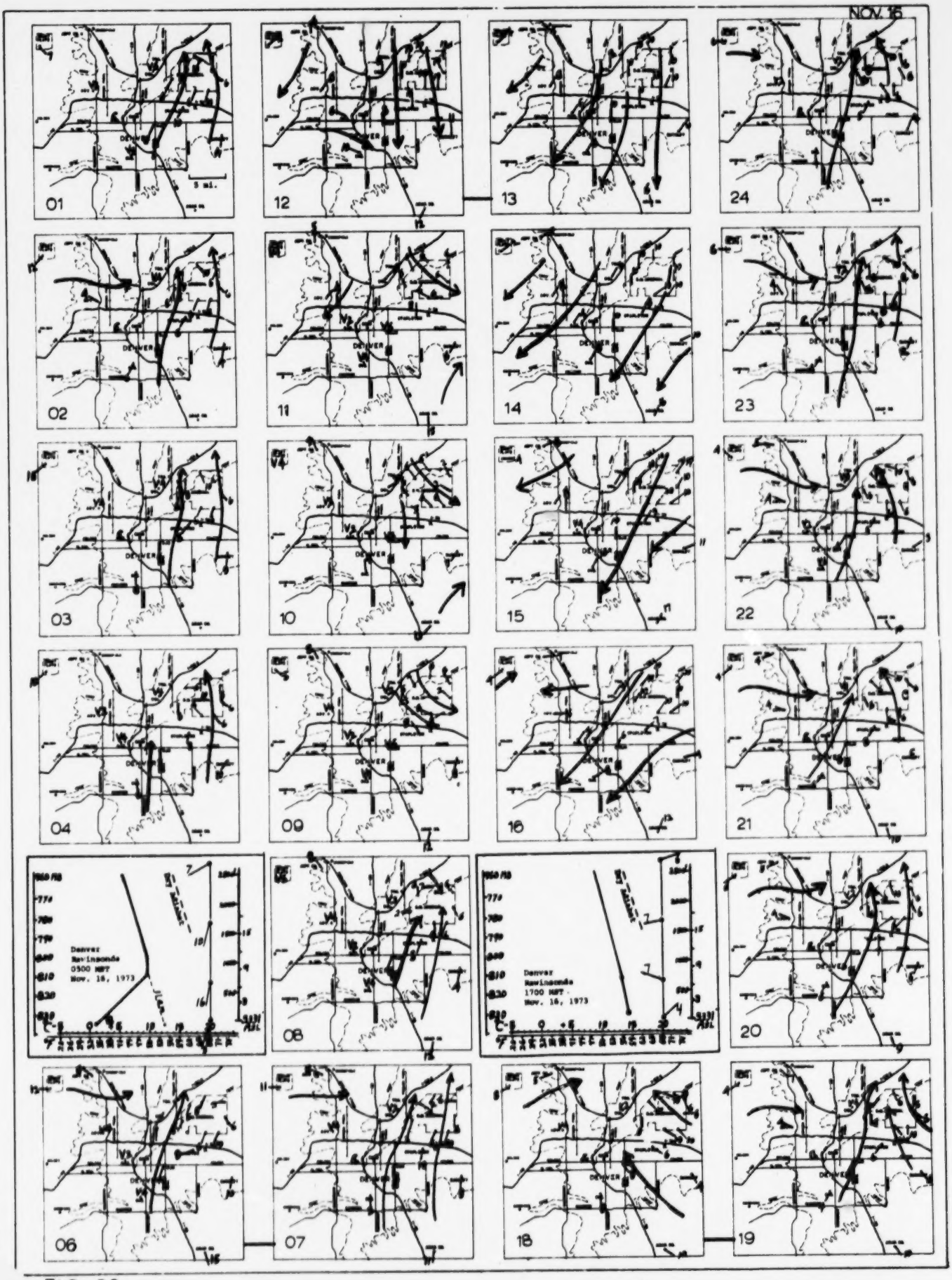

NOV. 16
01
12
13
24
02
11
14
23
03
10
15
22
04
09
16
21
Denver
Rawinsonde
0500 MST
Nov. 16, 1973
08
Denver
Rawinsonde
1700 MST
Nov. 16, 1973
20
06
07
18
19

FIG. 30

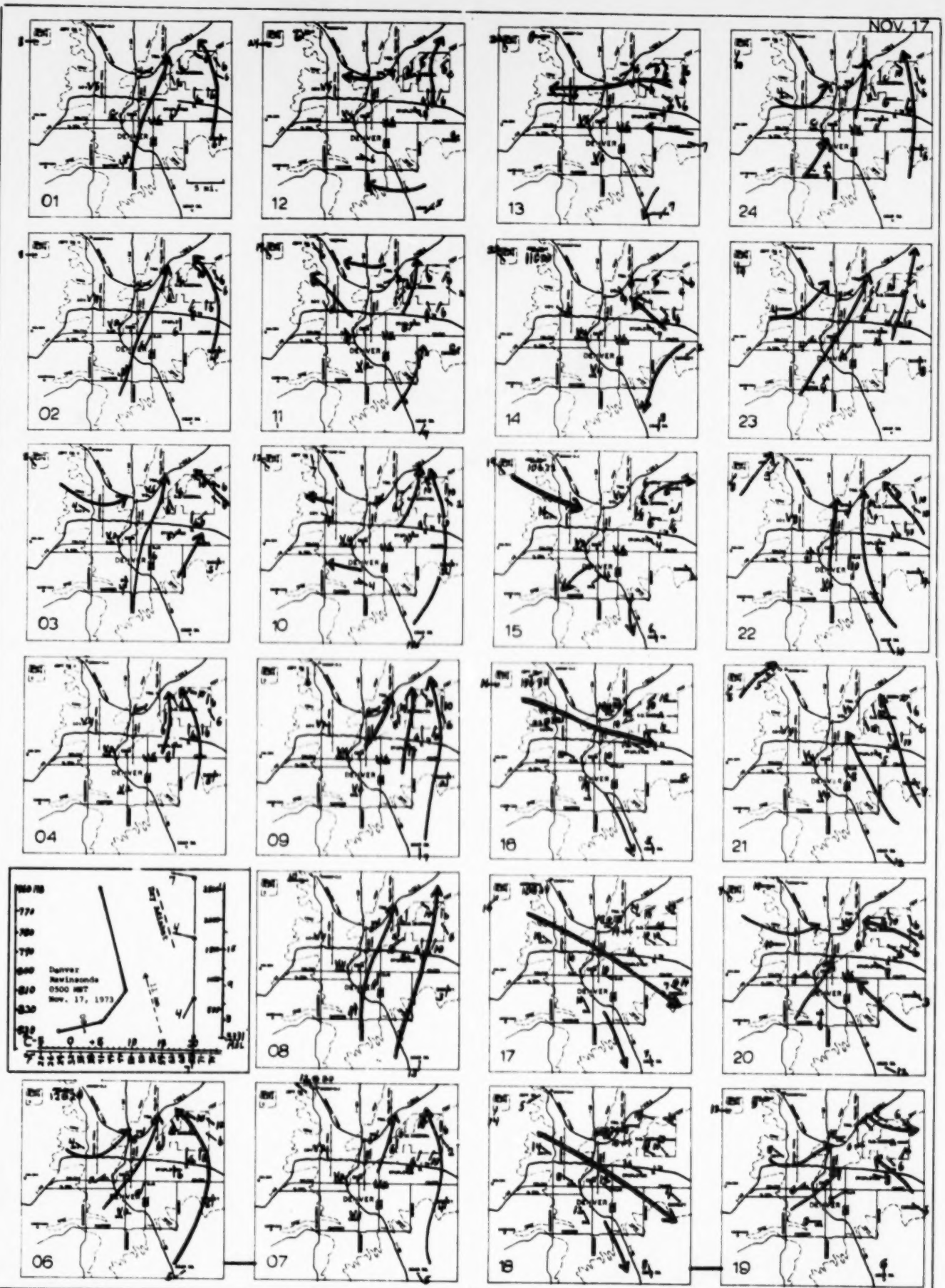

NOV. 17
01
12
13
24
02
11
14
23
03
10
15
22
04
09
18
21
Denver
Rawinsonde
0500 MST
Nov. 17, 1973
08
17
20
06
07
18
19

FIG. 31

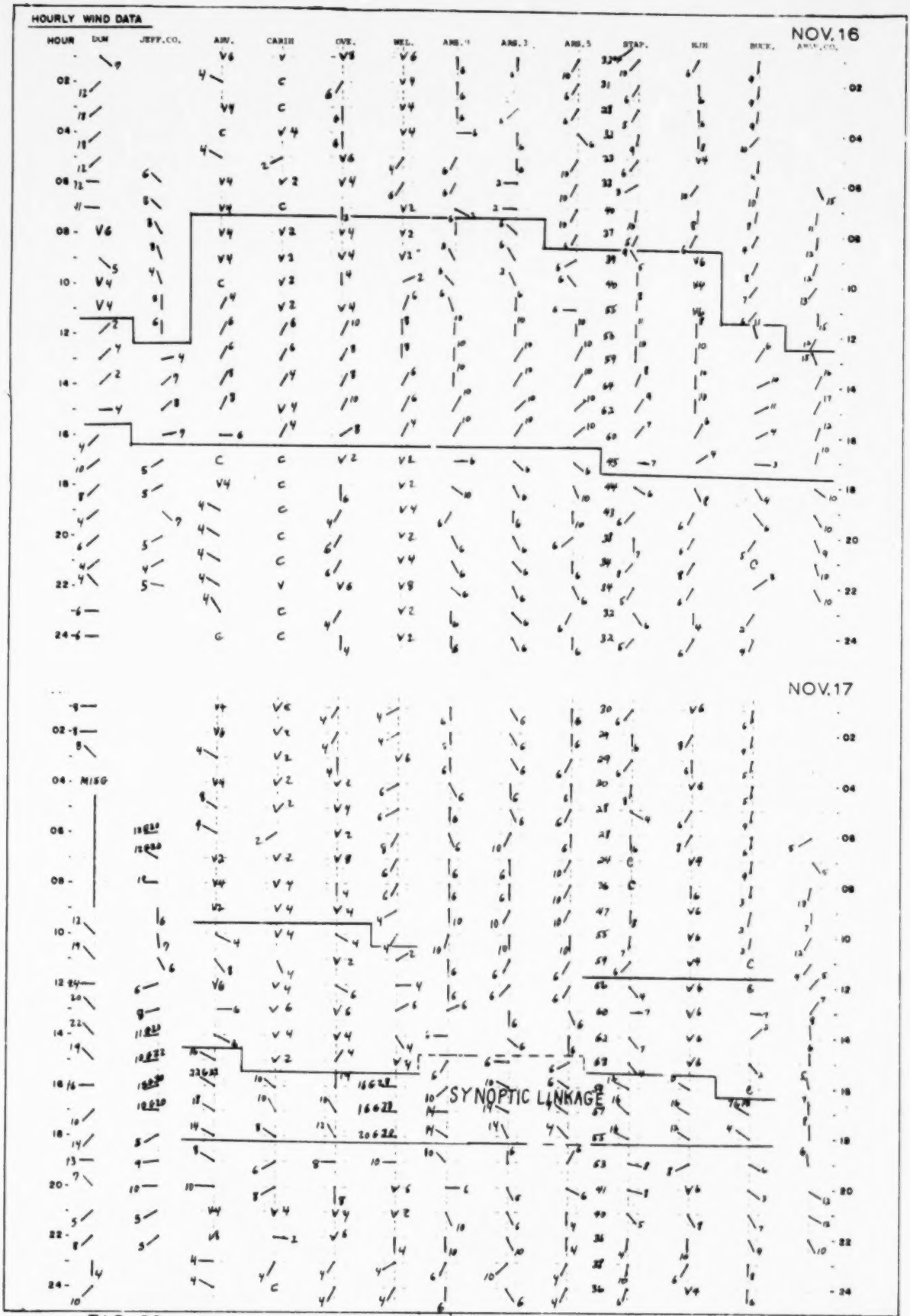

HOURLY WIND DATA
NOV. 16
NOV. 17
HOUR
DUN
JEFF. CO.
ARV.
CARIB
OVE.
MEL.
ARK. 1
ARK. 3
ARK. 5
STAP.
ELIN
BREK.
ARK. CO.
SYNOPTIC LINKAGE

FIG. 32

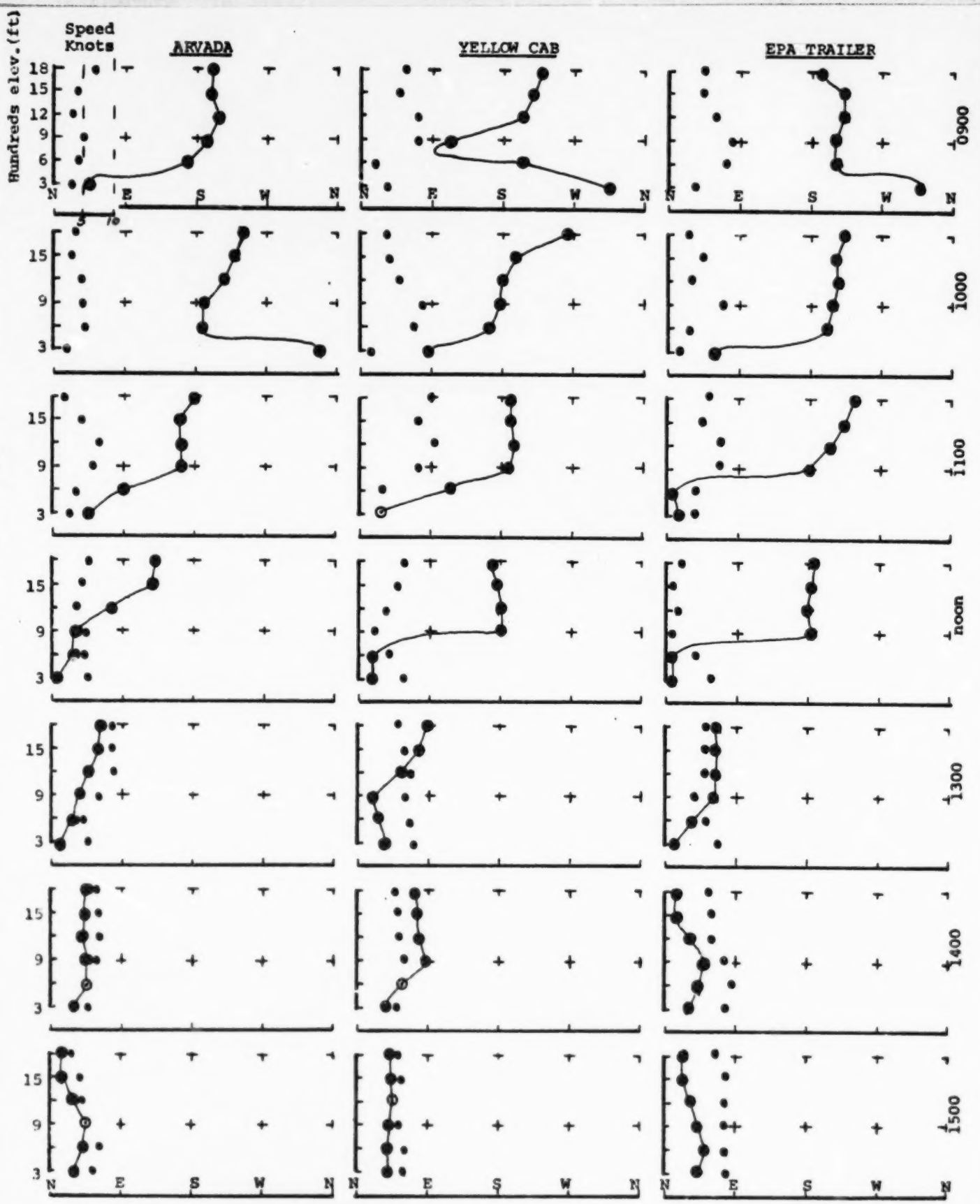


Figure 33. Sequential hourly pilot balloon runs showing wind speed and direction in lower 1800 feet, Nov. 16.

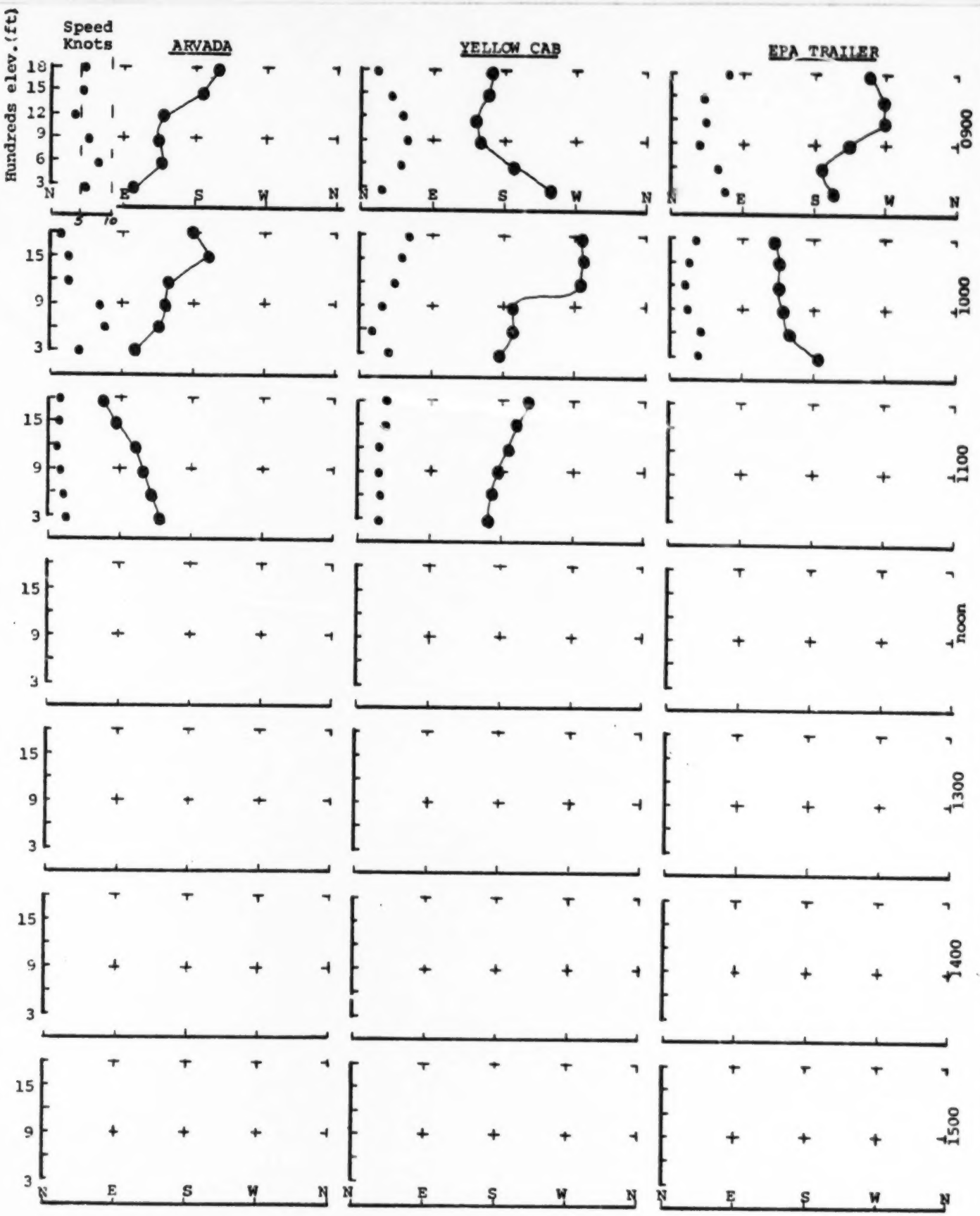


Figure 34. Sequential hourly pilot balloon runs showing wind speed and direction in lower 1800 feet, Nov. 17.

EPISODE DAYS NOVEMBER 20 - 21

This two-day period extended from the end of a snowstorm during the early morning hours of the 20th through a rather dense pollution day on the 21st. Since it began with a freshly cleaned air mass in the early forenoon of the 20th that day was not forecast to be a particularly bad pollution day. No pibal runs were made. One of the goals of the study period was to collect data for a period immediately following precipitation. The 20th certainly qualified in that category. Snowfall ended at Stapleton at 0520.

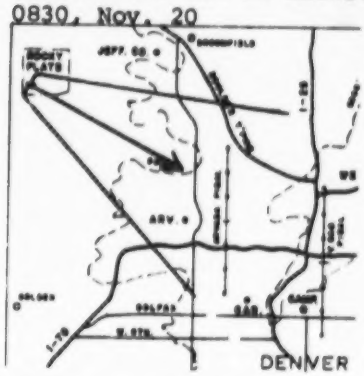
The sequence of pictures for the 20th taken by Dow Chemical personnel at Rocky Flats clearly shows a fresh snow covering at 0830 with a gradual buildup of some pollution during the day. See Fig. 35. The photographic record for the 21st, shown in Fig. 36, documents the manner in which polluted air was moved out of the city toward the west near noon.

The airflow charts for the 20th, shown in Fig. 37, confirm that the net flow for the entire day after the end of the snowstorm was toward some northerly component. The temperature sounding at 0500 of the 20th was taken before the snowstorm ended. There is a notable increase in temperature below 2500 feet between 0500 of the 20th and the same time on the 21st. See Fig. 38. An extra rawinsonde was made near noon on the 21st. This sounding helped confirm the rather abrupt change in airflow pattern and the change in vertical temperature profile between 0500 and 1200.

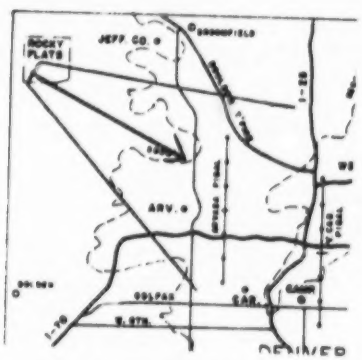
The individual hourly wind data record shown in Fig. 39 confirms previous comments. Note the drop below 70 percent relative humidity by 0800 of the 20th.

The pilot balloon record for the 21st is shown in Fig. 40.

Cloud cover and high plume rise from both cooling towers and stacks at Cherokee Power Plant as seen from Rocky Flats three hours after end of snowstorm; 0830, Nov. 20

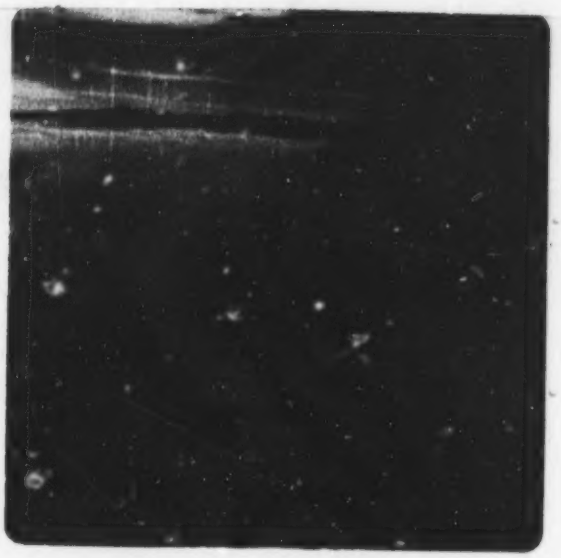


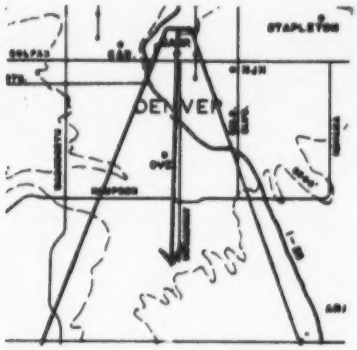
Four-hour buildup of air pollution over Denver as seen from Rocky Flats; 1230, Nov. 20



Seven-hour buildup of air pollution over Denver as seen from Rocky Flats; 1530, Nov. 20

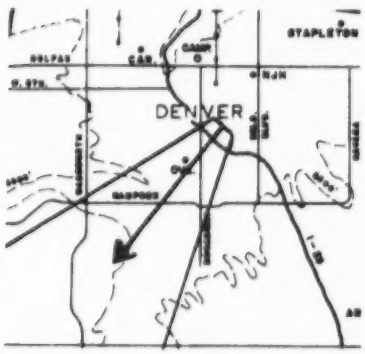
Figure 35. Progressive development with changes in depth, dimension, and location of pollution layer, Nov. 20.





North to south aerial photograph of pollution layer over Denver from 7000 ft. MSL;
1050, Nov. 21

Scene of rapid clearing from east to west as observed toward northwest from roof of Park Lane;
1240, Nov. 21



Scene of rapid clearning from east to west as observed toward southwest from roof of Park Lane;
1240, Nov. 21

Figure 36. Supporting photographs showing horizontal movement of pollution layer from east to west as synoptic airflow takes over near noon, Nov. 21.

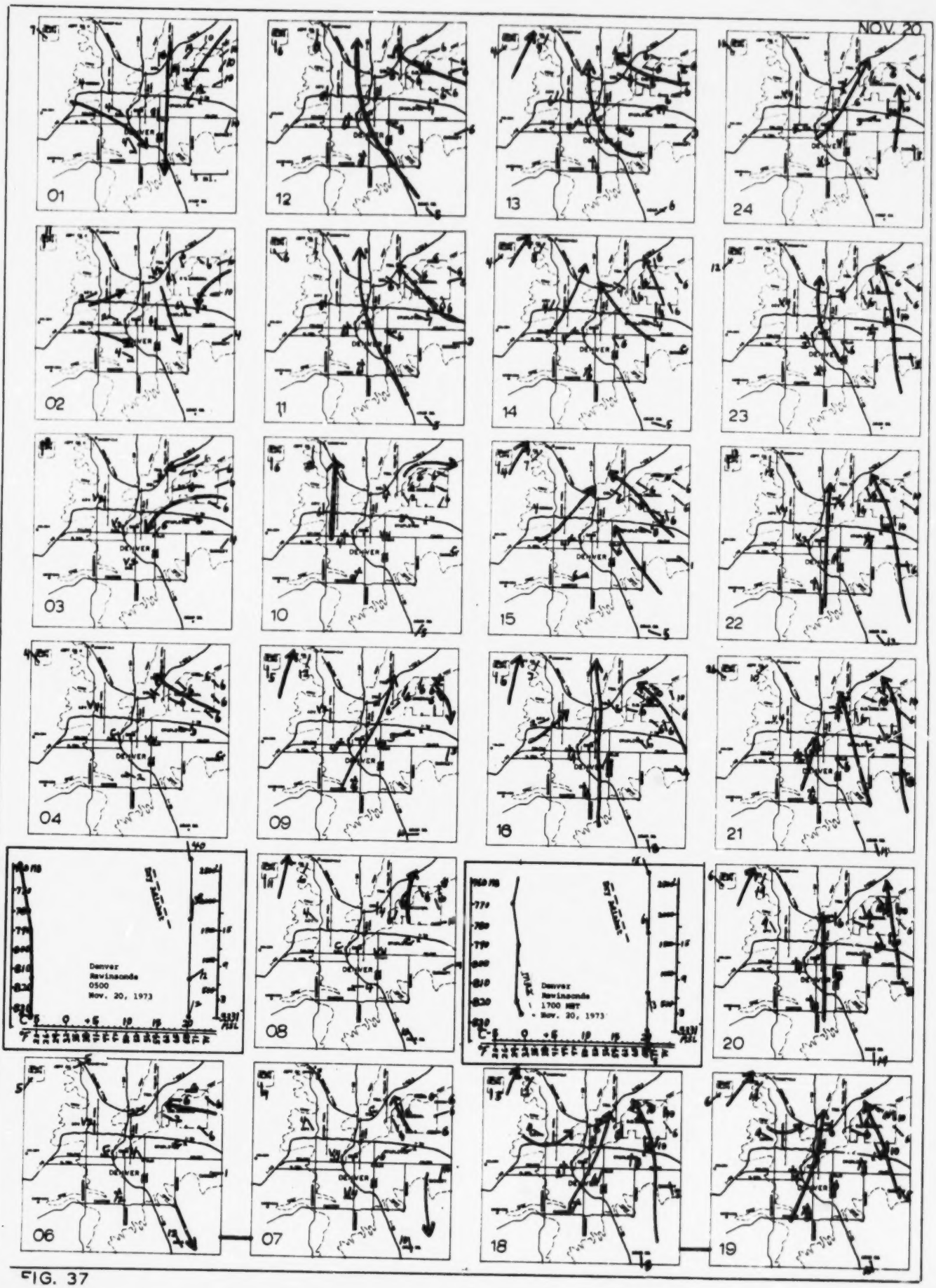

NOV. 20
01
12
13
24
02
11
14
23
03
10
15
22
04
09
16
21
Denver
Revinsonde
0500
Nov. 20, 1973
08
Denver
Revinsonde
1700 MST
Nov. 20, 1973
20
06
07
18
19

FIG. 37

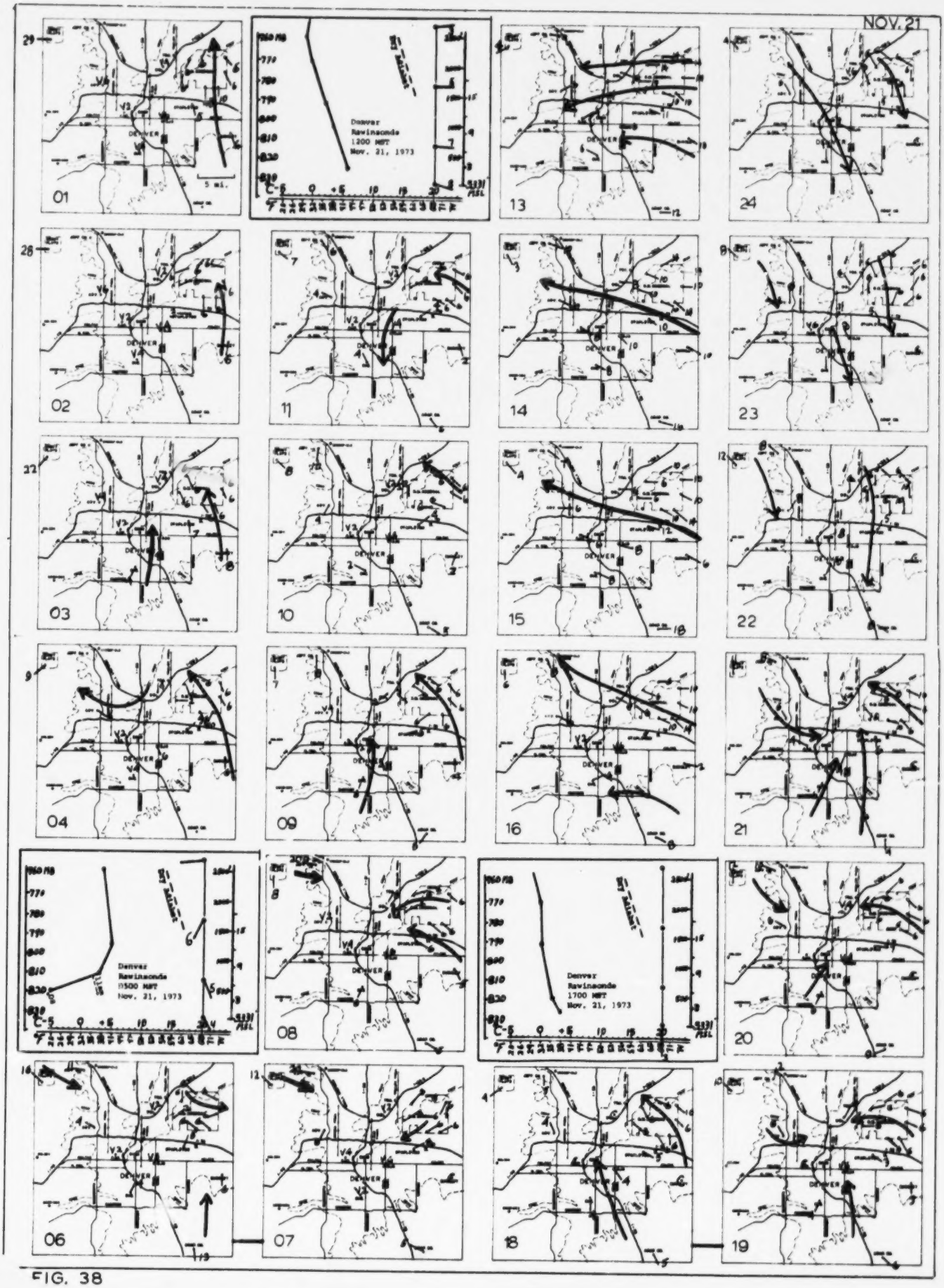

NOV. 21
01
02
03
04
06
07
08
09
10
11
13
14
15
16
18
19
20
21
22
23
24
Denver
Rawinsonde
1200 MST
Nov. 21, 1973
Denver
Rawinsonde
1500 MST
Nov. 21, 1973
Denver
Rawinsonde
1700 MST
Nov. 21, 1973

FIG. 38

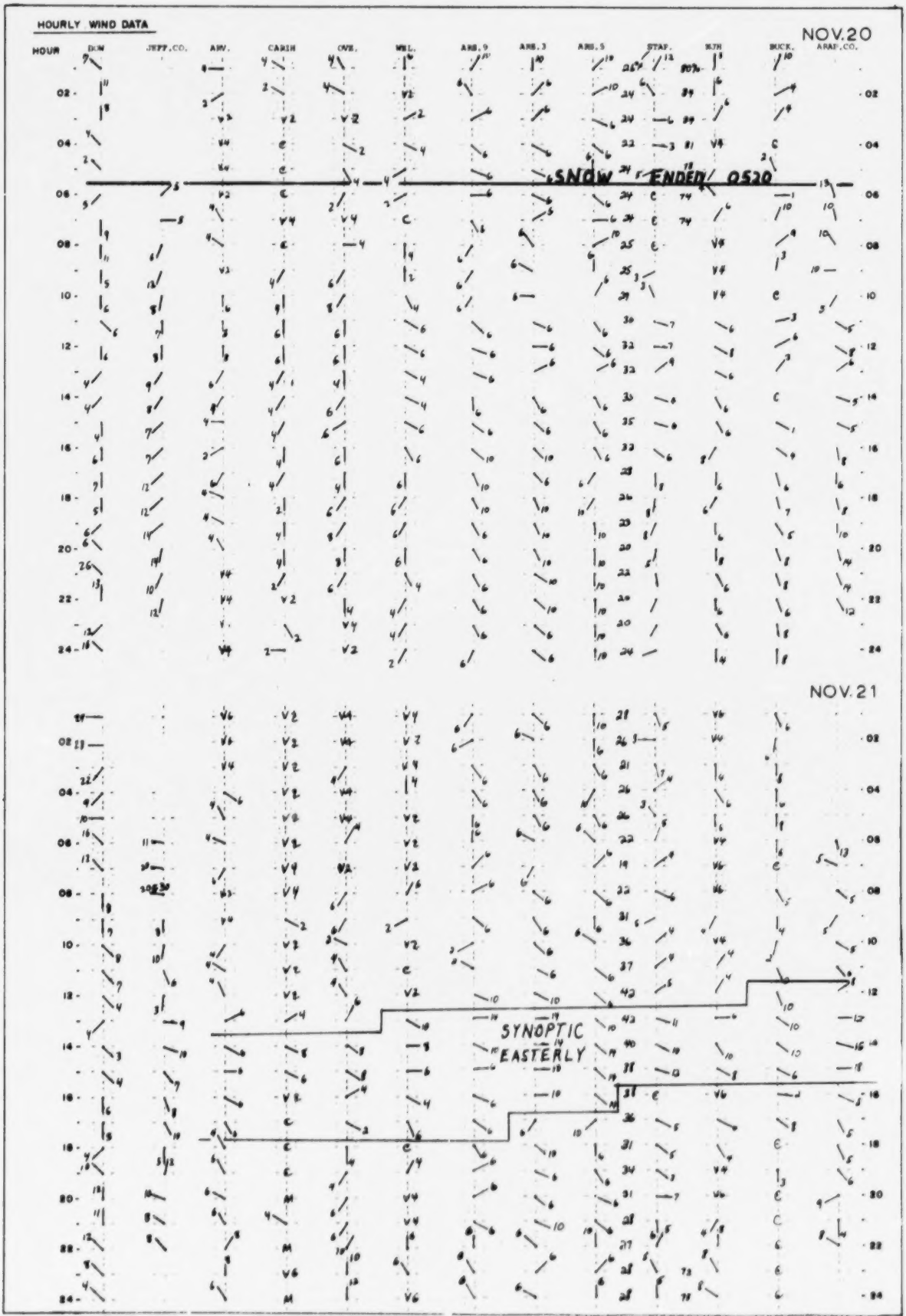

HOURLY WIND DATA
HOUR
DEN
JEFF.CO.
ARV.
CARIB
OVE.
WEL.
ARK.9
ARK.3
ARK.5
STAP.
KIM
BUCK.
ARAP.CO.
NOV.20
SNOW ENDED 0520
NOV.21
SYNOPTIC
EASTERLY

FIG. 39

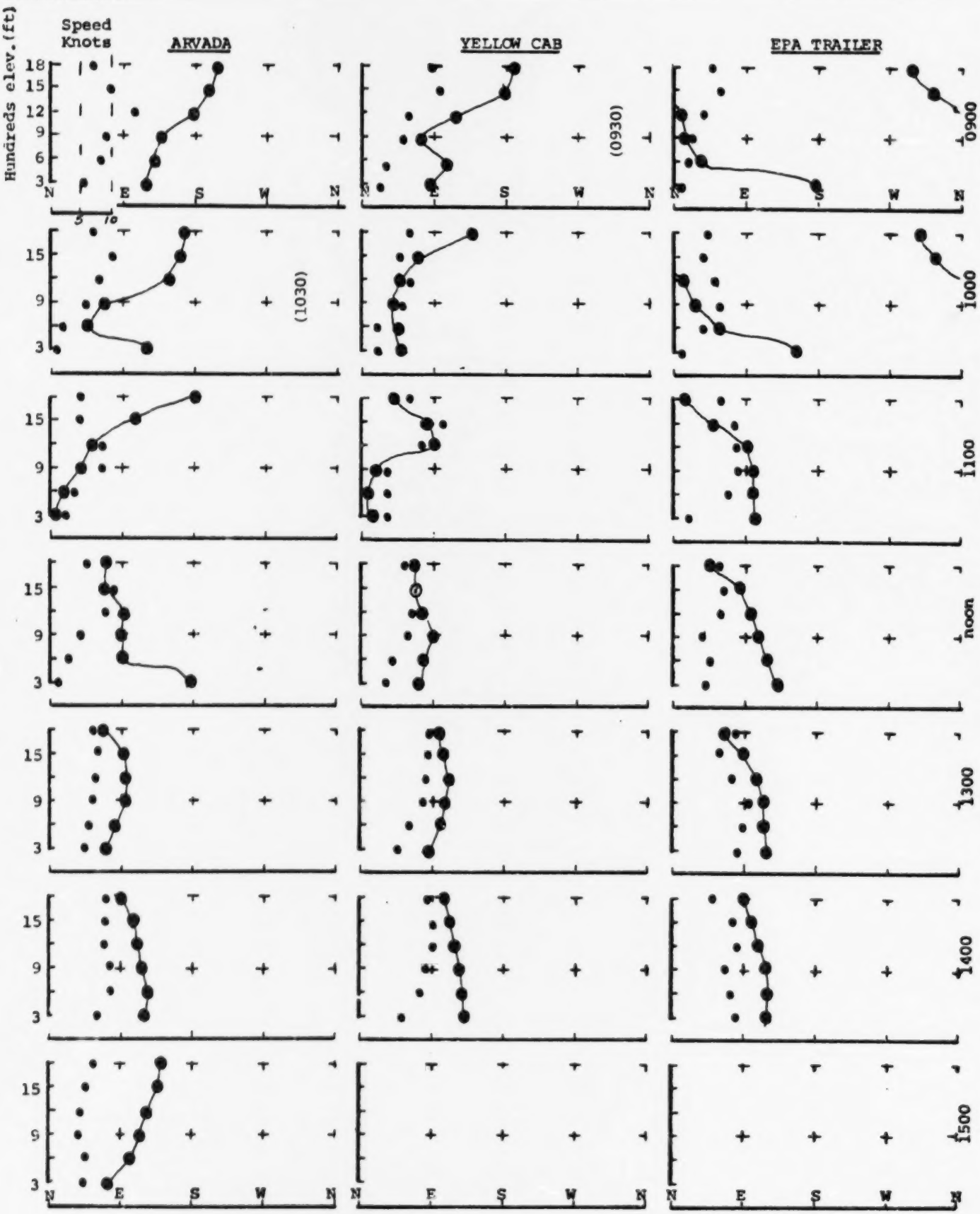


Figure 40. Sequential hourly pilot balloon runs showing wind speed and direction in lower 1800 feet, Nov. 21.

EPISODE DAY NOVEMBER 24

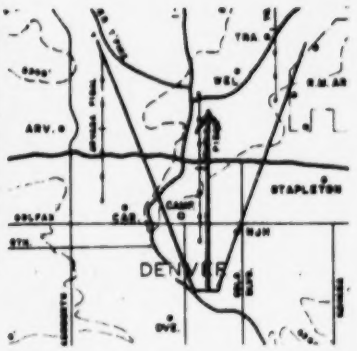
The airflow pattern of Saturday, November 24, produced one of the best records of typical daily sequence for a relatively bad air pollution day. The smaller level of automotive traffic on Saturday probably kept pollution levels below what they would have been on a Monday through Friday with the same airflow sequence. The photographic record in Fig. 41 verifies the gradual buildup of the pollution level near the north end of the city during forenoon hours. The third photograph taken in late afternoon across the south end of the metropolitan area shows that the more dense layer had moved to near the south end of the city by that time.

The hourly flow chart in Fig. 42 shows typical drainage prevailing from 0100 through 0600. Wind speeds were quite light and variable from 0700 through 0900. The reversal of airflow became well established for all stations north of Stapleton by 1100. There was a gradual turning of the wind to move air toward the foothills from 1300 through 1600 with velocities generally less than 10 mph. Downslope drainage flow again established itself by 1800.

The hourly wind record in Fig. 43 reconfirms the patterns shown on the hourly flow chart. Note that the beginning of north to south flow takes place at Welby and Station 9 at the Arsenal between 0600 and 0700. The turn-around takes place progressively southward and at higher elevations along both shoulders of the river valley as the day progresses. There is no sharp distinction to indicate any precise time that downslope drainage begins.

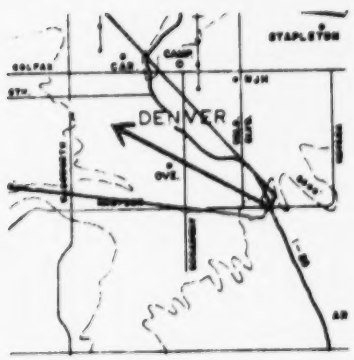
The pibal records shown in Fig. 44 contain north to south flow most of the time. However, some near calm winds permitted wide variability in directions at both 1000 and 1100.

Reproduced from best available copy.



Scene of air pollution as observed toward north from roof of Park Lane:
0930, Nov. 24.

Same scene:
1150, Nov. 24



Scene of later afternoon pollution toward west-northwest from Valley Highway and Hampden Blvd.:
1600, Nov. 24

Figure 41. Progressive development and changes in depth, dimension, and location of pollution layer, Nov. 24.

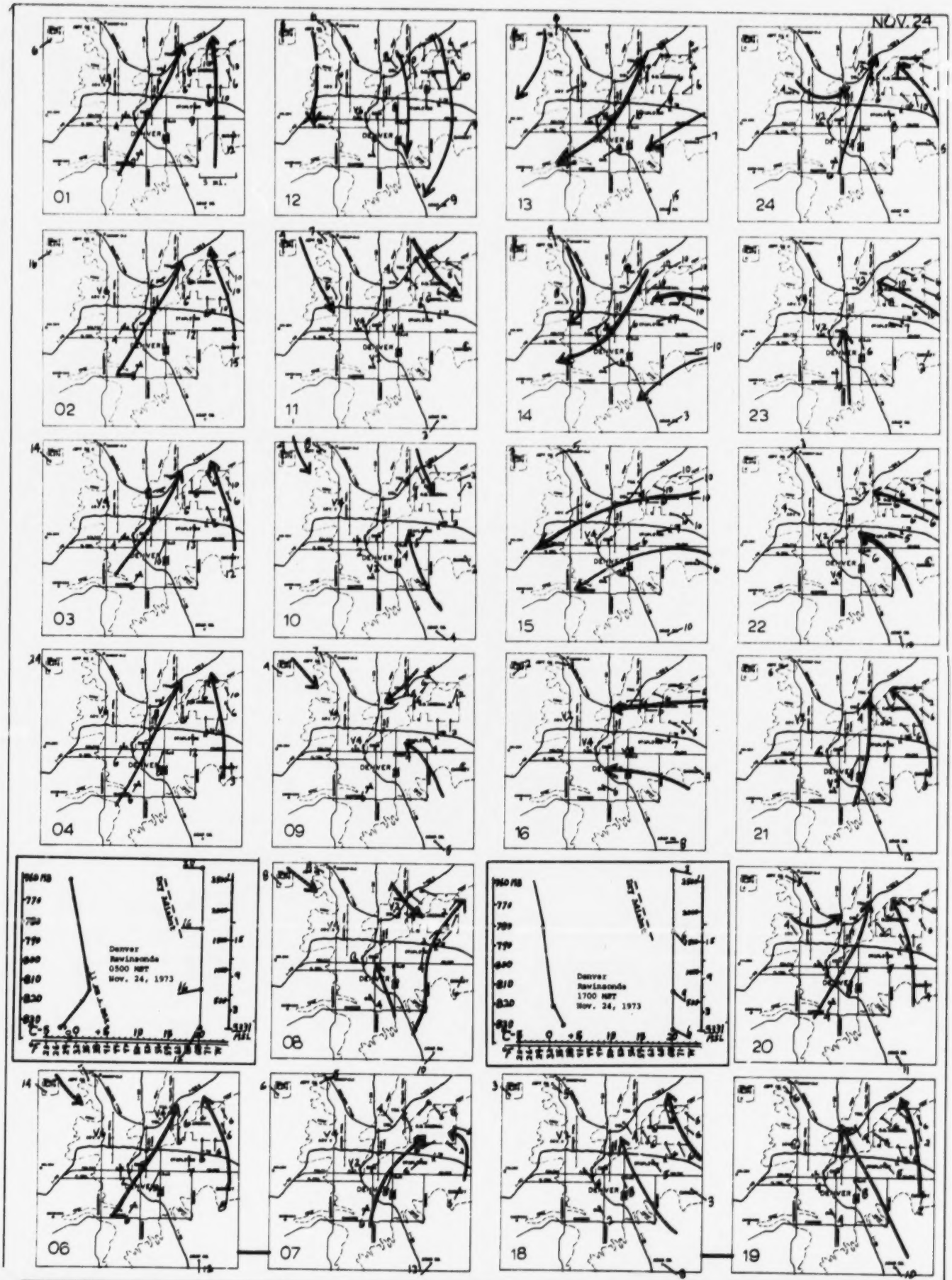

NOV. 24
01
12
13
24
02
11
14
23
03
10
15
22
04
09
16
21
Denver
Rawinsonde
0500 MST
Nov. 24, 1973
Denver
Rawinsonde
1700 MST
Nov. 24, 1973
08
20
06
07
18
19

FIG. 42

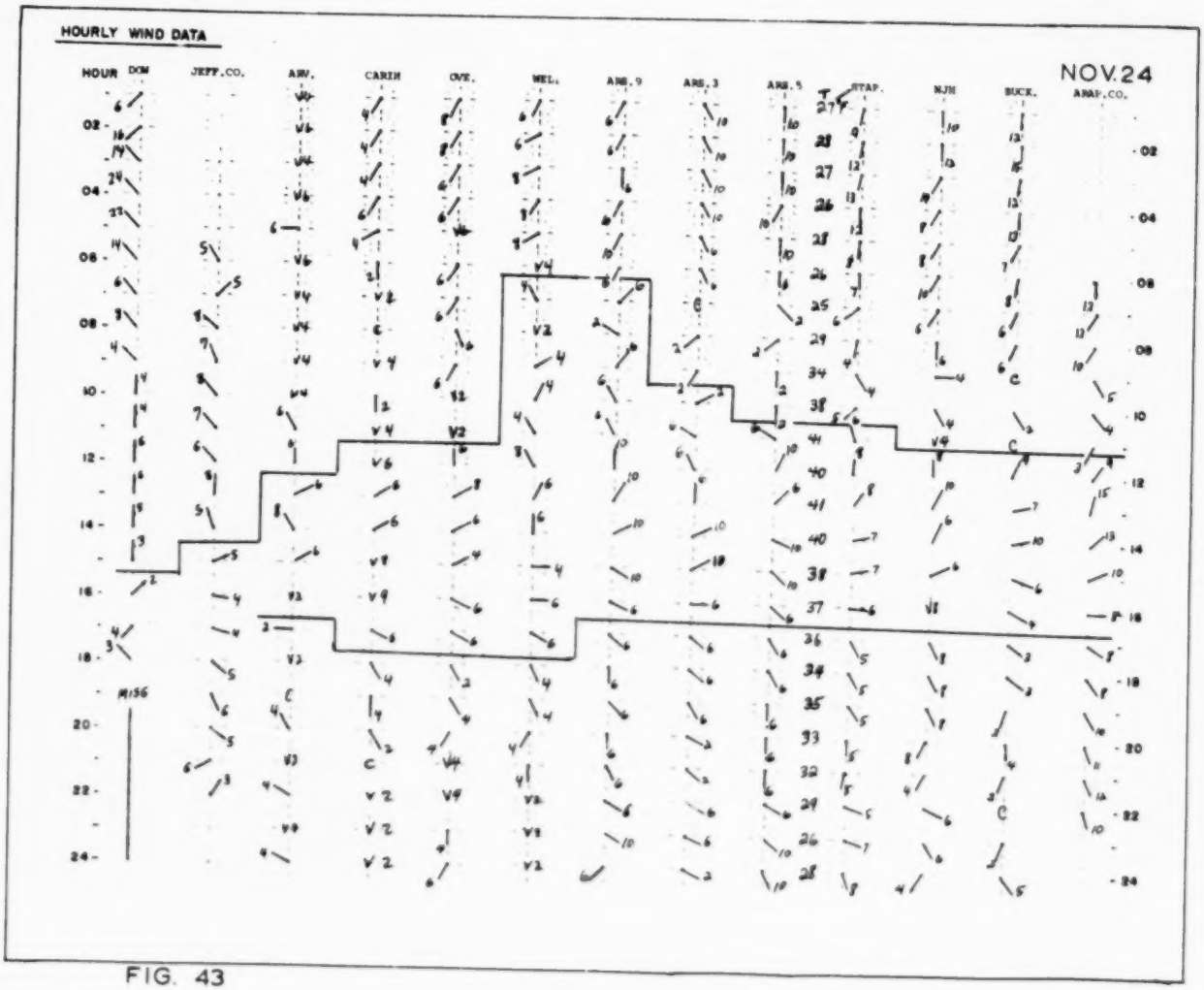

HOURLY WIND DATA
NOV. 24
HOUR
DOV
JEFF. CO.
AIRV.
CARIH
OVE.
WEL.
ANS. 9
ANS. 3
ANS. 5
STAF.
NJH
BUCK.
ANAP. CO.
MISS

FIG. 43

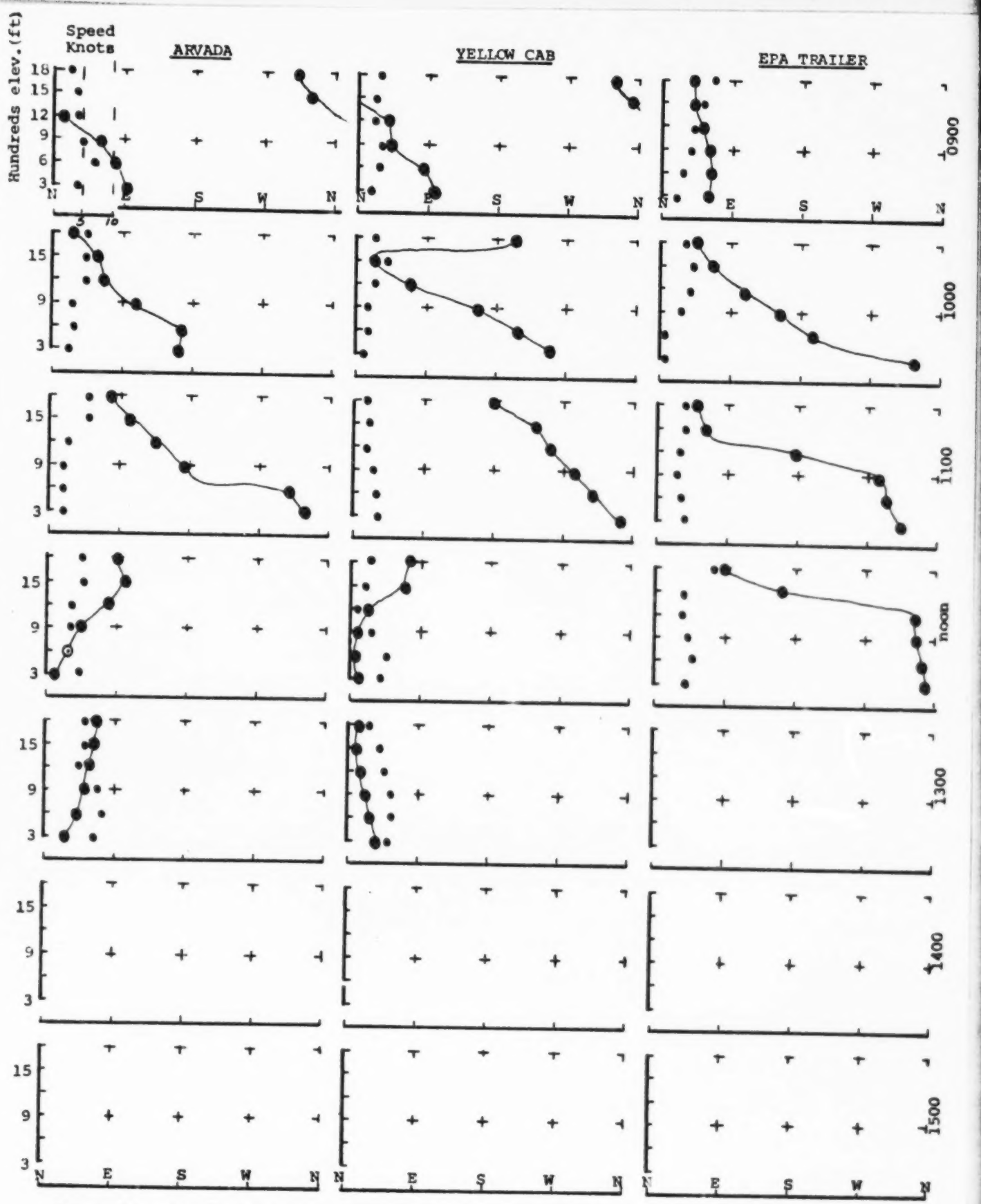


Figure 44. Sequential hourly pilot balloon runs showing wind speed and direction in lower 1800 feet, Nov. 24.

EPISODE DAYS NOVEMBER 29 - 30

These two episode days occurred after sampling equipment mounted in the EPA Trailer had been dismantled. There were no pilot balloon runs on these days. However, the surface wind patterns have been collected. Both days were relatively dense air pollution days. Samples of the photographic record are presented in Fig. 45. The gradual increase in air pollution depth between 1400 and 1600 feet on the 29th as seen from Rocky Flats is shown in the first two photographs of Fig. 45. The temperature inversion was not broken on that day. There was a deeper layer of pollution with somewhat less density at 1530 on November 30.

The hourly airflow charts shown in Figs. 46 and 47 indicate that both days were near typical in the reversal of downslope drainage in the cooler part of the day, followed by upslope flow during the warmer part of the day. Temperature inversions were not eliminated on either day. However, the afternoon temperature profile on the 30th shows that the layer of polluted air should have been near 1700 feet deep at the time of the maximum temperature.

The hourly wind sequence shown in Fig. 48 indicates the timing of the repeatable pattern of daily airflow exchange for each of the several stations. Even with the relatively low wind speeds on these two days the motion of air at both Jefferson County Airport and at Rocky Flats tends to not be a consistent part of the flow pattern near the center of the Platte River Valley.

Time-lapse photographs were taken at both the Federal Center and Buckley ANGB on the 29th but only at Buckley on the 30th.

Reproduced from best available copy.

Air pollution layer over Denver as seen from Rocky Flats:
1400, Nov. 29

Same scene:
1600, Nov. 29

Same scene, following day:
1530, Nov. 30.

Figure 45. Two photographs showing progressive development and changes in depth and dimension of pollution layer during afternoon hours of Nov. 29, plus one view of the pollution layer in mid-afternoon on Nov. 30.

Reproduced from
best available copy.

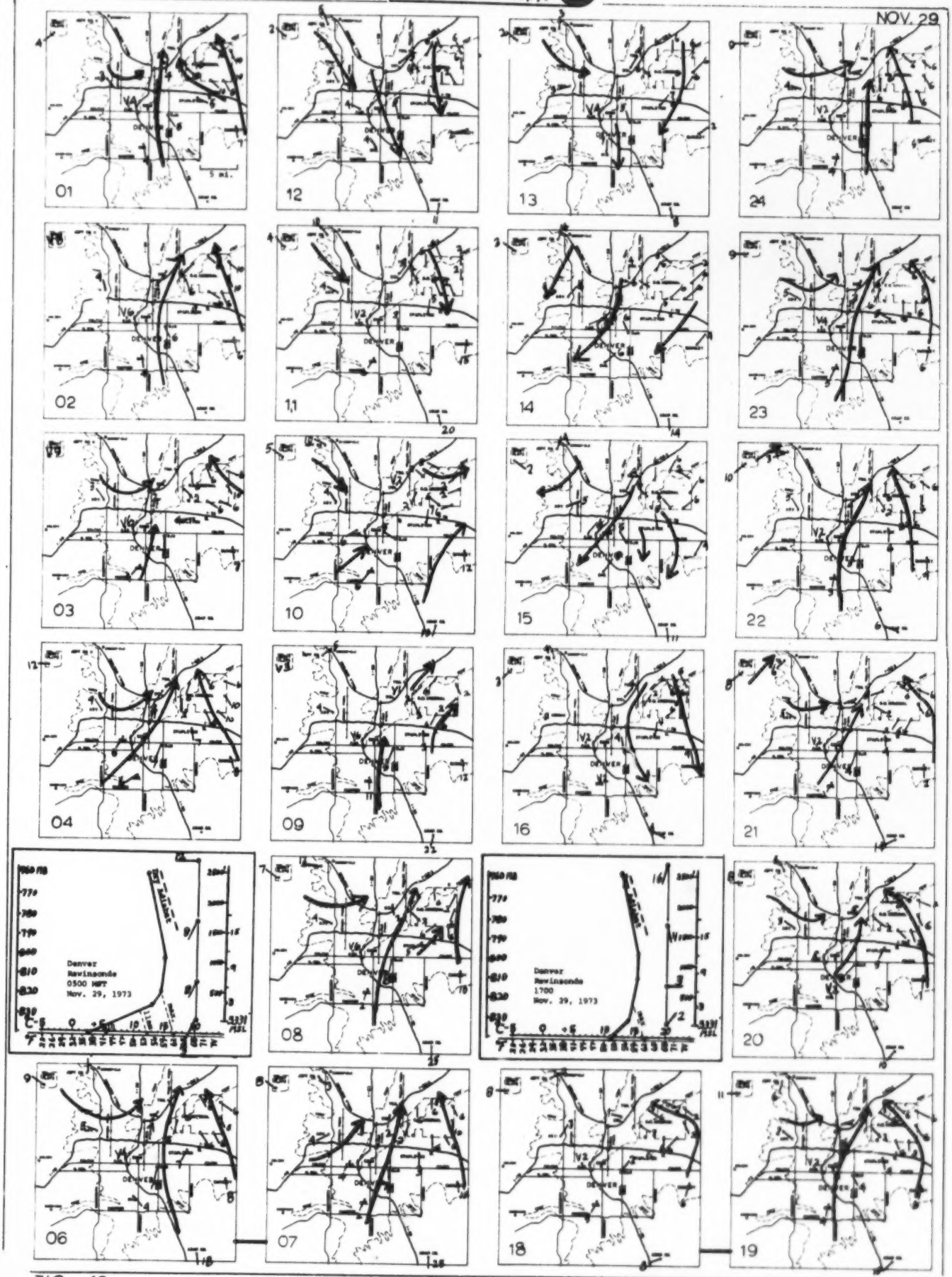


FIG. 46

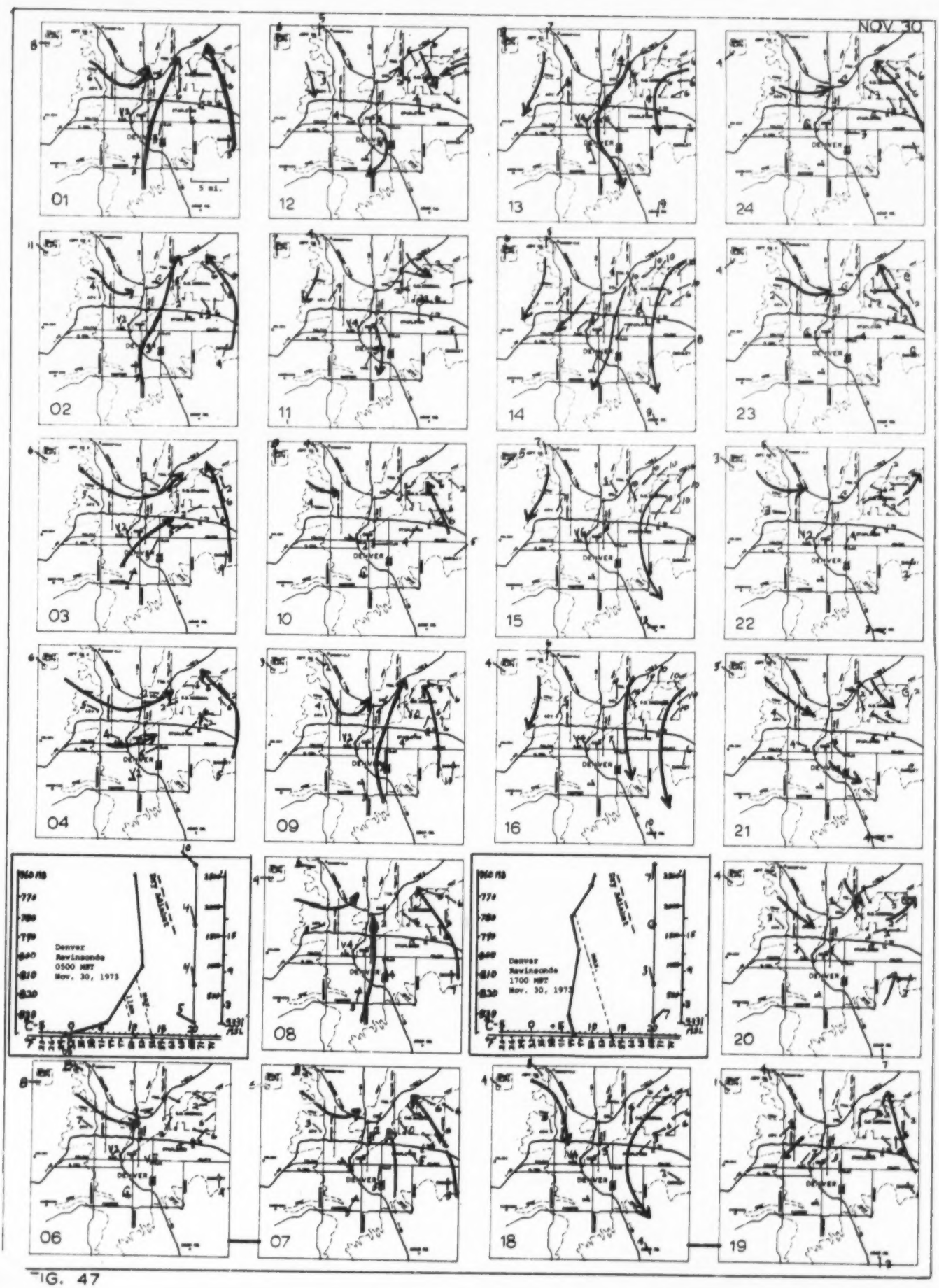

NOV. 30
01
12
13
24
02
11
14
23
03
10
15
22
04
09
16
21
Denver
Rawinsonde
0500 MST
Nov. 30, 1973
08
Denver
Rawinsonde
1700 MST
Nov. 30, 1973
20
06
07
18
19

FIG. 47

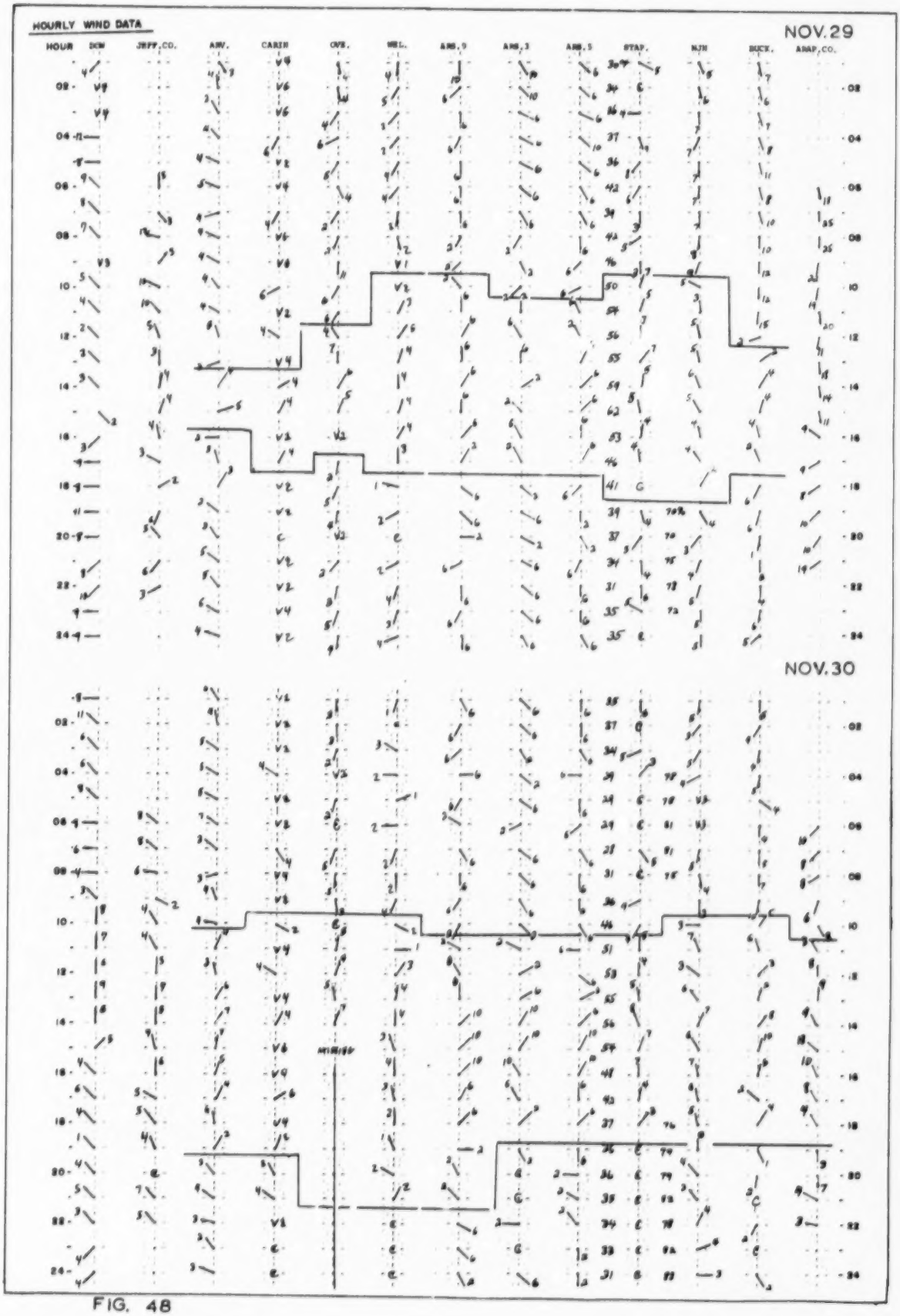

HOURLY WIND DATA
NOV. 29
NOV. 30
HOUR
DEN
JEFF. CO.
ARV.
CARIN
OVE.
WEL.
ARK. 0
ARK. 3
ARK. 5
STAP.
NJN
BUCK.
ARAP. CO.

FIG. 48

ACKNOWLEDGEMENTS

Many cooperating agencies and interested persons collected data on an intermittent basis during November. Only a limited number of individuals who were particularly helpful in collecting meteorological data are listed here.

Personnel from the Regional Office of EPA included William Cogger, James Harris and James Lewis.

Personnel from the Colorado Department of Health, Air Pollution Control Division, who very willingly worked on weekend days included Arthur Adams, Charles Bray, Richard Fox, William Retallack, L. Todd Reynolds, Norman Weigel and David Wickham.

Students from Metropolitan State College who assisted in data collection were Steven Geoghegan, Ronald Rutherford, Timothy Smith and Dennis Tarrin.

Aerial photographic missions were conducted by photographer Charles E. Grover.

Clarence Evereson of the Bureau of Reclamation and Sgt. James Summey of Buckley ANGB generously volunteered their time to operate the time-lapse cameras.

Many surface photographs were taken by Fred Crawford of Dow Chemical Company at Rocky Flats and David Nertherby of the Sheraton Inn-Denver Airport.

The author acknowledges with thanks the willing cooperation of many other persons and companies who collected wind and temperature data from various locations throughout the Denver metropolitan area.